Stable Throughput Regions in Wireless Networks

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Contents

Abstract

We present a review of the notion of stability and of stable throughput regions in wireless networks, with emphasis on network layer cooperation between interacting users. After a brief introduction, we examine in detail specific instances of the stability issue. These instances differ from each other in terms of the network, channel and traffic models they use. What they share is the notion of how stability is affected by node cooperation, as well as the notion of "interacting queues" that makes the stable throughput analysis difficult and often intractable. This review is intended to provide a reference point for the rich set of network control problems that arise in the context of queue stability in modern and future networks.

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1
Introduction

This volume examines the fundamentals of stable throughput in wireless networks. The origins of the problem can be found in the area of random multiple-access channels, where "bursty" exogenous traffic enters the network queues, and the performance of the system is measured in terms of the rate at which data is delivered from the source terminals to their respective receivers, while guaranteeing that the queues in the network do not grow unbounded.

Ever since Shannon's 1948 seminal paper that laid the foundations of information theory [55], the dominant fundamental question has been how to maximize the rate of reliable data transmission from a source to a destination. The main focus has been on the source-channel-destination (i.e., single-link) model of communication. This has led to significant advances in the fields of coding, compression, modulation, and detection, thereby enabling the development of the communication infrastructure that we use today. When it comes to the field of communication "networks," the same information-theoretic approach deals with the determination of the best *joint rates* at which different users can transmit over a shared channel. However, this has not yet made a comparable mark in terms of improving our understanding of the ultimate performance limits of networks. This is partly because of the focus that information theory places on saturated users, that is, users who have unlimited depositories of data to transmit. This ignores the bursty nature of traffic, as well as the role of latency in communication. In turn, it has given rise to other measures of rate performance, especially in the context of networks. Moreover, while the data *primitives* in information theory are endless strings of symbols, the basic data units in networks are groups of finite number of symbols called *packets*. One such measure considered by the "networking" community is the *throughput* metric, which, in multi-user systems, is a multi-dimensional region of rates expressed in packets/slot that is achievable over a given network. Even though the users are assumed to be saturated here as well, this quantity measures the set of packet flows that can be sustained in the network, and is usually much easier to characterize than the information-theoretic rate measures.

The need to analyze bursty traffic in networks gave rise to the development of the notion of *stable throughput*, which is another measure of rate (in packets/slot). It is defined for users that are not backlogged, i.e., their transmission queues may sometimes be empty. In such networks, users receive bursty traffic, which is queued up in their buffers while awaiting transmission. These queues need to be stable, that is their size should not grow without bound. There are various definitions of the queueing-theoretic notion of stability, and the precise definition that we use in this volume is provided later on in this chapter. It is important to note that this measure need not coincide with the aforementioned throughput measure. In fact, in many cases it outer-bounds the latter. The reason for this is that in a network (especially, but not only, a wireless network) the queues of the users may be *coupled*, in other words, they may *interact* with each other. Thus, when one user's queue empties under the stability requirement, (as it must with probability one) it ceases (albeit temporarily) to compete for communication resources with the other users. Therefore, the other users can achieve higher rates as long as the queues of one or more users remain idle. This subtle interaction will become clear later.

A large volume of literature already exists that documents the efforts related to the determination of the stable throughput regions of wireless networks, as discussed in Chapter 2. Most of the early analysis was for the so called, *collision* channel model, in which multiple simultaneous transmissions result in destructive collision and loss of packets. This is a simple model that characterizes the interference-limited environments well. However, it fails to characterize properly the dynamics of the wireless environment and the capabilities of decoding equipment. Recent work has incorporated more realistic wireless channel models in which packets could survive the interference caused by concurrent transmissions if the received signal-to-interference-and-noise ratio (SINR) exceeds the threshold required for successful decoding at the receiver.

Another aspect of wireless networks that has received significant attention recently is the notion of cooperation among nodes to improve overall network performance. Cooperation, as we will see, affects the achievable rate measures as well. We will examine several different instantiations of node cooperation, including its use in *cognitive* shared channels, multicast communication, and finally in the case where there is channel state information available to the users.

We start by presenting a model for a point-to-point wireless link, and then provide a precise definition for stability and maximum stable throughput that will be used throughout this volume.

1.1 Point-to-Point Link

We model the wireless link as a discrete-time-slotted communication channel. It consists of a source node s and a destination node d, as shown in Figure 1.1. Data arrives at the source s in the form of packets of fixed length independently according to a Bernoulli process with an average arrival rate of λ packets per time slot. The transmission duration of one packet is equal exactly to one time slot, and the packets are buffered at the source s in a queue Q of unlimited capacity. Because not all packets are successfully received, an error-control mechanism is needed. We assume the use of a simple automatic repeat query (ARQ) scheme, whereby a packet is retransmitted until the transmission from

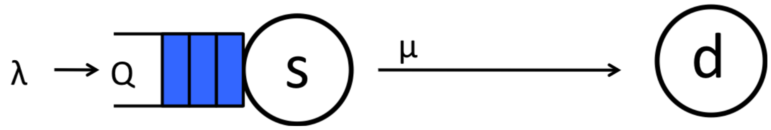

Figure 1.1: A point-to-point wireless communication channel.

s is successful at destination d. This assumes the existence of a 1-bit perfect feedback channel that provides information about packet success or failure instantly to the source. We assume that the probability distribution of time until successful delivery is *exponential* with mean $1/\mu$ packets per slot. More importantly, the arrival and transmission processes are assumed to be independent.

Such a wireless link can be described in standard queueing-theoretic nomenclature as a discrete-time $M/M/1$ queueing system [5] that consists of a single queueing station with a single server. The ratio of the average arrival rate to the average service rate is called the utilization factor $\rho = \lambda/\mu$, and is an indication of how busy the server is. The probability that there are n customers in the system (equivalent to n packets in the buffer) is given by

$$p_n = \rho^n(1-\rho), \qquad n = 0, 1, ...$$

Therefore, it can be easily seen that the probability that a queue Q is non-empty is given by

$$\mathbf{P}[Q > 0] = \lambda/\mu. \tag{1.1}$$

The analysis of an $M/M/1$ system, as well as several other related systems, is based on the theory of Markov chains. More on Markov chains and their relationship to $M/M/-$ type queueing systems can be found in [5].

1.2 Queue Stability and Stable Throughput

A fundamental issue in a queueing system is the behavior of its queue size. Before we define what we mean by stability, we will describe how a single server queue evolves over discrete time. Let Q^t represent the queue length of a single-server discrete-time queue over integer time slots $t \in \{0, 1, 2, ...\}$. Then, Q^t evolves according to the stochastic equation shown below.

$$Q^{t+1} = [Q^t - Y^t]^+ + X^t,$$

where Y^t is the number of departures in slot t, X^t is the number of arrivals in slot t, and $[x]^+ = \max(0, x)$. Here, Y^t and X^t can be thought of as stochastic arrival and server processes that are sequences of real valued random variables defined over the time slots $t \in \{0, 1, 2, ...\}$. The arrival rate of packets into the queue is defined as the first moment of X^t, i.e., $\lambda = \mathbf{E}(X^t)$, which we assume exists and is finite.

Stability of a system is defined in [65] as the ability to keep a quantity of interest in a bounded region, i.e., the existence of a limiting distribution for this quantity of interest. Assuming queue length as the quantity of interest, we define queue stability as follows.

Definition 1.1. A queue Q^t that evolves over discrete time slots $t \in \{0, 1, 2, ...\}$ is said to be stable if

$$\lim_{t\to\infty} \mathbf{P}[Q^t < x] = F(x) \quad \text{and} \quad \lim_{x\to\infty} F(x) = 1, \tag{1.2}$$

where $F(x)$ is the limiting distribution function.

Furthermore, the queue Q^t is said to be *sub-stable* [65] if a weaker condition holds, namely, if

$$\lim_{x\to\infty} \lim_{t\to\infty} \inf \ \mathbf{P}[Q^t < x] = 1.$$

The relationship between stability and sub-stability can described as follows: a sub-stable queue is stable if a limit exists for the distribution function, shown in (1.2), while a stable queue is necessarily sub-stable [34]. If a queue is not sub-stable, it is *unstable*. For example, Meyn and Tweedie showed in [40] that if Q^t is an aperiodic and irreducible Markov chain defined on a countable state space, then sub-stability is equivalent to stability, since a limiting distribution exists for such Markov chains. However, it was also shown in [40] that, this might not be true if the Markov chain is defined over a general state space.

Furthermore, this formal definition of stability can easily be extended to the multidimensional process $\mathcal{S} = \{Q_1^t, Q_2^t, ...\}$.

For queues where the arrival and service processes are strictly jointly stationary,[1] Loynes' theorem [34] states that the queue Q^t is stable if and only if the average arrival rate λ is strictly less than the average service rate denoted by μ, i.e., $\lambda < \mu$. If $\lambda > \mu$, the queue is unstable.[2] The *maximum stable throughput* of the single server discrete time queue is defined as the maximum arrival rate λ for which the queue is stable. We use this stability result and the notion of stable throughput throughout this manuscript, although several other variations of the notion of stability also exist, which in many cases turn out to be equivalent.

1.3 Other Rate Measures

In this section we discuss two other rate measures that are commonly used in the context of point-to-point links.

1.3.1 Maximum Throughput

While stable throughput analysis provides insight into a system with bursty data arrivals, we also consider the case in which a source node always has data to transmit (i.e., its queue never empties). We define the *maximum throughput* of the queueing system as the maximum number of packets on average that are successfully received by the destination per time slot, in which the packet queue of the source node is saturated. In this sense, the maximum throughput of the link is the maximum service rate μ in packets/slot that can be achieved over the link.

[1] This is an assumption we make throughput this volume.

[2] In the critical case of when $\lambda = \mu$, i.e., when the average arrival rate just equals the average rate of service, deciding whether a queue is stable or not is rather complicated and is beyond the scope of this volume.

1.3.2 Capacity

The traditional notion of Shannon *capacity* deals with the maximum achievable data rate in bits/sec that can be transmitted reliably[3] over a communication resource such as a point-to-point link. It is known, for example, that the information-theoretic capacity of a band-limited additive Gaussian noise channel is given by

$$C = W\ \log_2\left(1 + \frac{P}{N_0 W}\right) \quad \text{bits/sec} \tag{1.3}$$

where P is the signal power at the receiver, and N_0W is the noise power[4] at the receiver, while W denotes the channel bandwidth.

The idea of maximum throughput discussed earlier has some similarity to, and usually coincides with, the information-theoretic concept of capacity of point-to-point links, after a change of units to convert packets to bits and slots to seconds. Both rate measures require that source terminals have an infinite backlog of data to transmit, which differs from the case of bursty traffic. We also note that many problems in single-user, as well as multi-user, information theory remain open, including the capacity determination for the classical single-relay channel, which is known only for some special cases [39, 7, 17, 26].

1.4 Organization of the Volume

The rest of the volume is organized as follows. Chapter 2 provides a review of the different rate regions associated with multiple-access systems. We describe the landscape in terms of the relationships among these rate regions, and briefly discuss what is known and what problems are still open. Next, in Chapter 3, we investigate the notion of packet-based cooperation in multiple-access systems, and present the stable-throughput results for a two-user cooperation system under scheduled access as well as random access. We extend the idea of network layer cooperation in Chapter 4, in which, we present the stability analysis

[3] By reliably, we mean, with an arbitrarily small error probability.

[4] N_0 is therefore, the noise power spectral density, i.e., noise power per unit bandwidth.

for a cognitive cooperation system, where the secondary (lower priority) user cooperates by acting as a relay and forwards some of the primary (higher priority) user's packets. We show how cooperation is beneficial to both primary as well as the secondary users by comparing the cooperative scheme with that of a non-cooperation scheme where the secondary user does not relay the primary user's information. Furthermore, we assume that the receivers are equipped with multipacket reception capability, which is a more general wireless packet reception model than the collision channel. In Chapter 5, we generalize the cognitive cooperative system to incorporate the transmission of multicast traffic. Based on the stability analysis, we demonstrate the benefits of cooperation in terms of increase in the stable-throughput region as well as the improvement of packet delay, and we identify the transmission strategies that maximize the stable-throughput region for different levels of multipacket reception capability. In Chapter 6, we investigate the impact of channel state information on the stable-throughput region of the cognitive cooperative system by assuming that the secondary user has access to the channel state information. Finally, in Chapter 7, we present our conclusions.

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