Performance Characteristics of a Reservation MAC Protocol with Multiple Data Channels

February 2008

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IEEE Sensors Applications Symposium
Atlanta, GA February 12-14, 2008

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I. INTRODUCTION

II. PROTOCOL DESCRIPTION

III. TRAFFIC STATISTICS

IV. RESERVATION PERFORMANCE

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Introduction: Background

- In an already overcrowded radio frequency (RF) spectrum, multiple access of the same RF spectrum by numerous wireless users in a coordinated manner is the key to enter into efficient and effective communications.
- A medium access control (MAC) scheme used in wireless ad hoc networks must cope with the time-varying network topology and the physical channel impairments.
- These impairments could result from propagation losses, multi-path fading, interference, terrain conditions, topology variations, etc.
- The Carrier Sense Multiple Access (CSMA) with Collision Avoidance (CA) protocol, a reservation protocol MAC, appears to be one of the current favorites for ad hoc networks operating in dynamic environments, because of its simplicity and flexibility.

Introduction: CSMA/CA Protocol Overview

- In the CSMA/CA protocol, the total network resource is generally divided into separate frequency channels and/or time slots for Request-to-Send/Clear-to-Send (RTS/CTS) control access and data packet transfers.
- Using the CSMA/CA protocol, radios compete to reserve the right to transmit a packet using relative short control packets, rather than directly competing for data transmissions using relatively long data packets.
- Once a reservation is made, a single data channel is usually used for the data transmission.
- The performance characteristics of the reservation MAC protocol with a single data channel is well known.
- However, its performance for multiple data channels has not been clearly characterized for practical applications.

Introduction: CSMA/CA with Multiple Data Channels

- In this paper, we extend the CSMA/CA with a single data channel (CSMA/CA_SD) to the CSMA/CA with multiple data (MD) channels (CSMA/CA_MD).
- In the CSMA/CA_SD, control access packets and data packets share the same single channel resource, while in the CSMA/CA_MD once a reservation is made, the data transmission can use any of the available data channels.
- This paper derives the performance achievable by the CSMA/CA_MD, and their relative performance measures are compared.
- The results can easily be applied by users to assess their operational needs.

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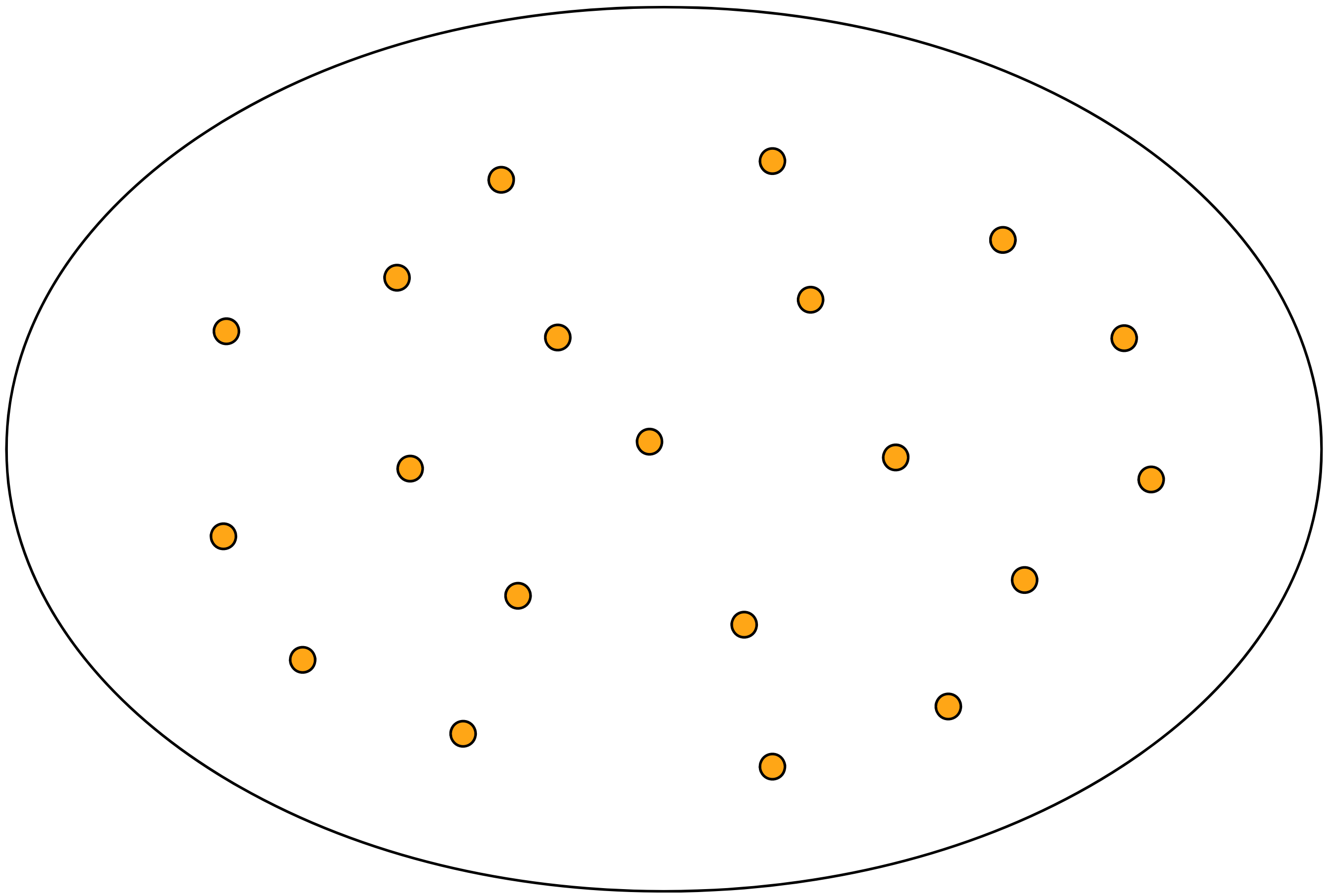
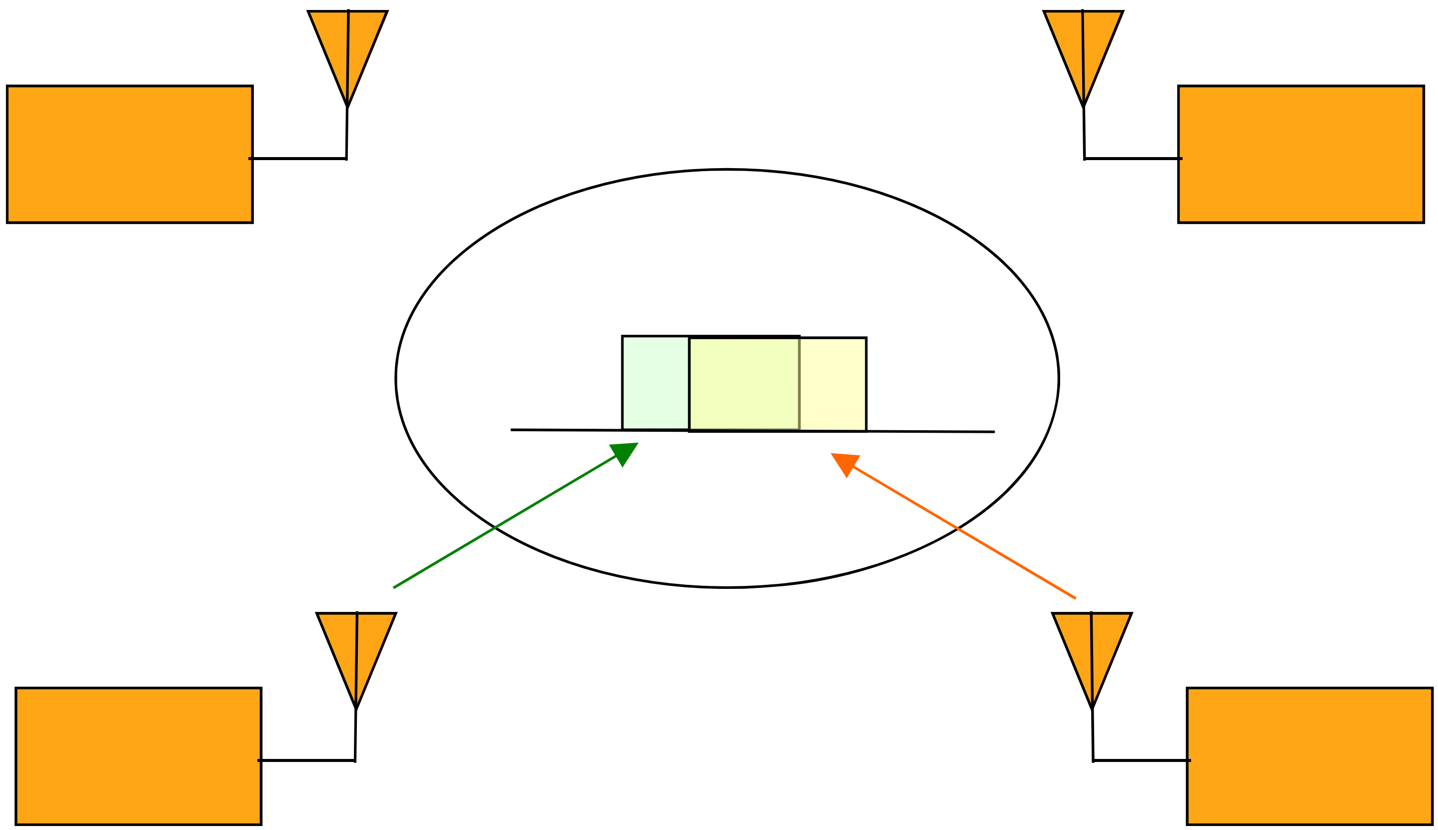
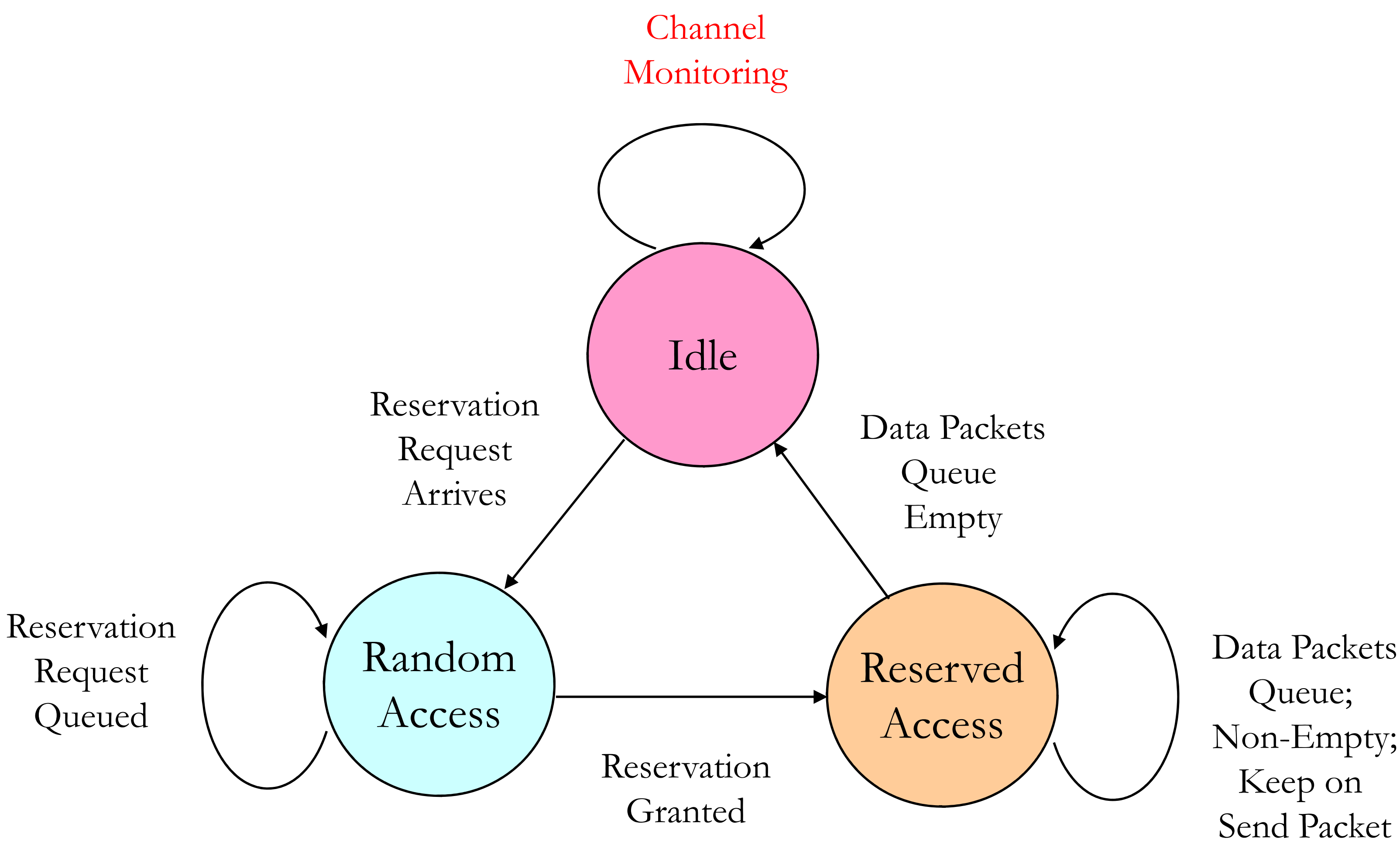
Sensors Connected by Wireless Communications



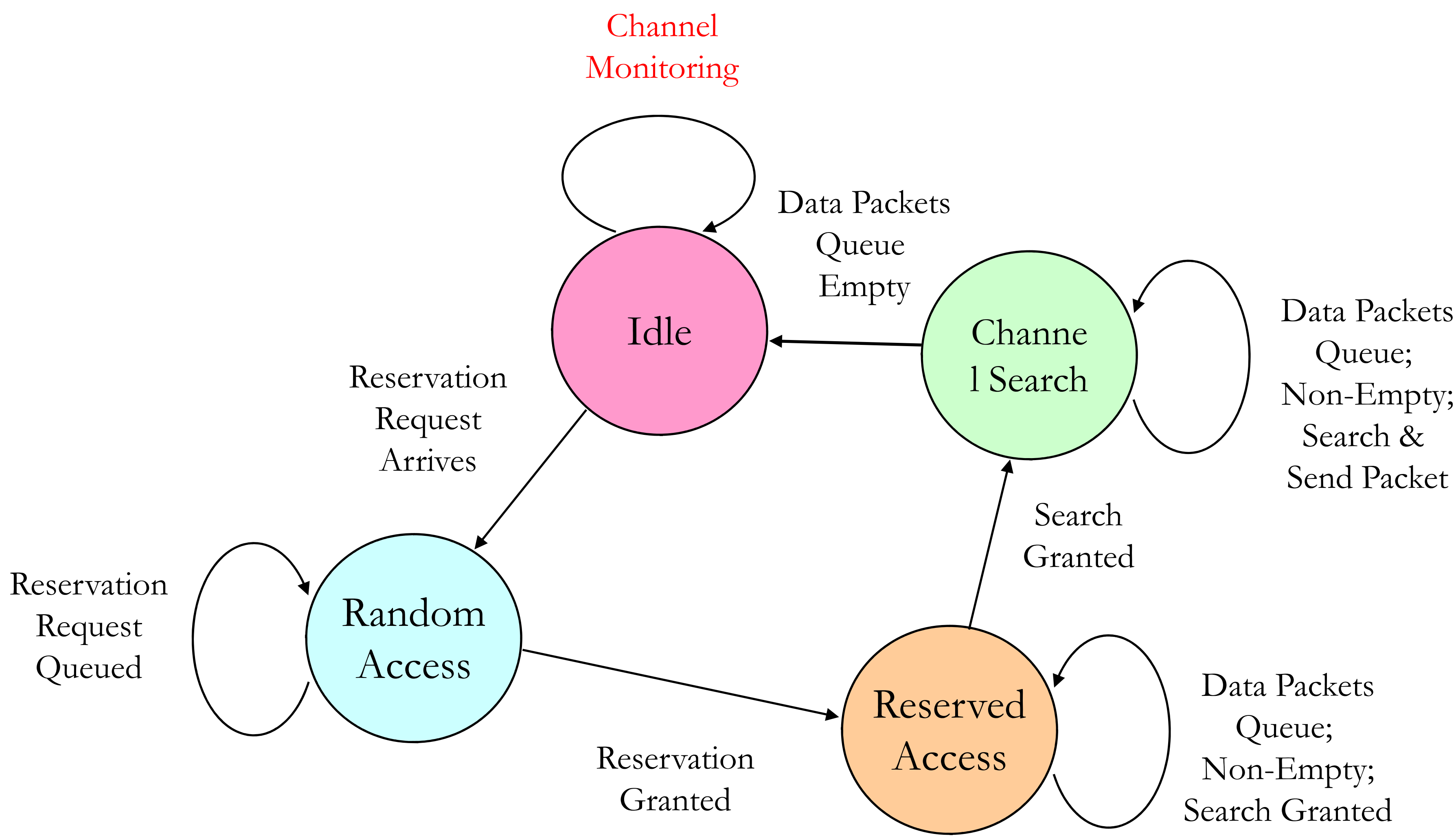
Packet Collision in Space



CSMA/CA_SD: State Transition Diagram



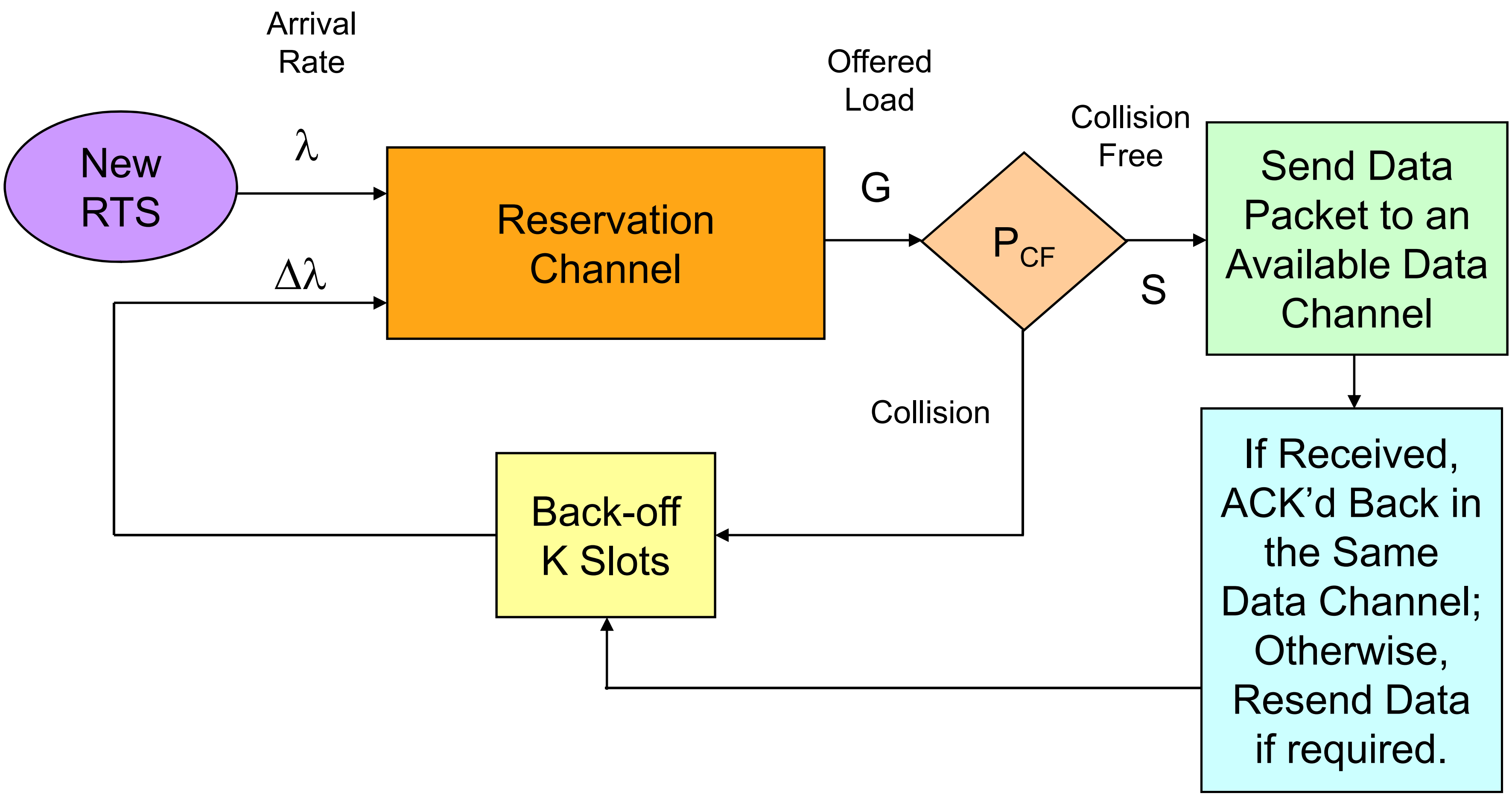
CSMA/CA_MD: State Transition Diagram



CSMA/CA_MD PROTOCOL DESCRIPTION

- When a node wants to send data to another, it first sends a short RTS packet to the destination.
- The receiver responds with a short CTS packet containing the necessary handshake and channel information.
- On receipt of the CTS, the sender sends its queued data packet(s) in an agreed data channel of available data channels. If the sender does not receive a CTS after a timeout, it resends its RTS and waits for a reply.
- Upon successful receipt of the data packet, the receiver returns an immediate link Acknowledgment (ACK) packet on the same data channel, notifying the sender regarding the reception and quality status.
- The exchange terminates with the ACK. If no ACK is received, the sender tries again. The number of retries is programmable and is initially set to a pre-assigned value.

CSMA/CA_MD Flow Diagram and Parameters



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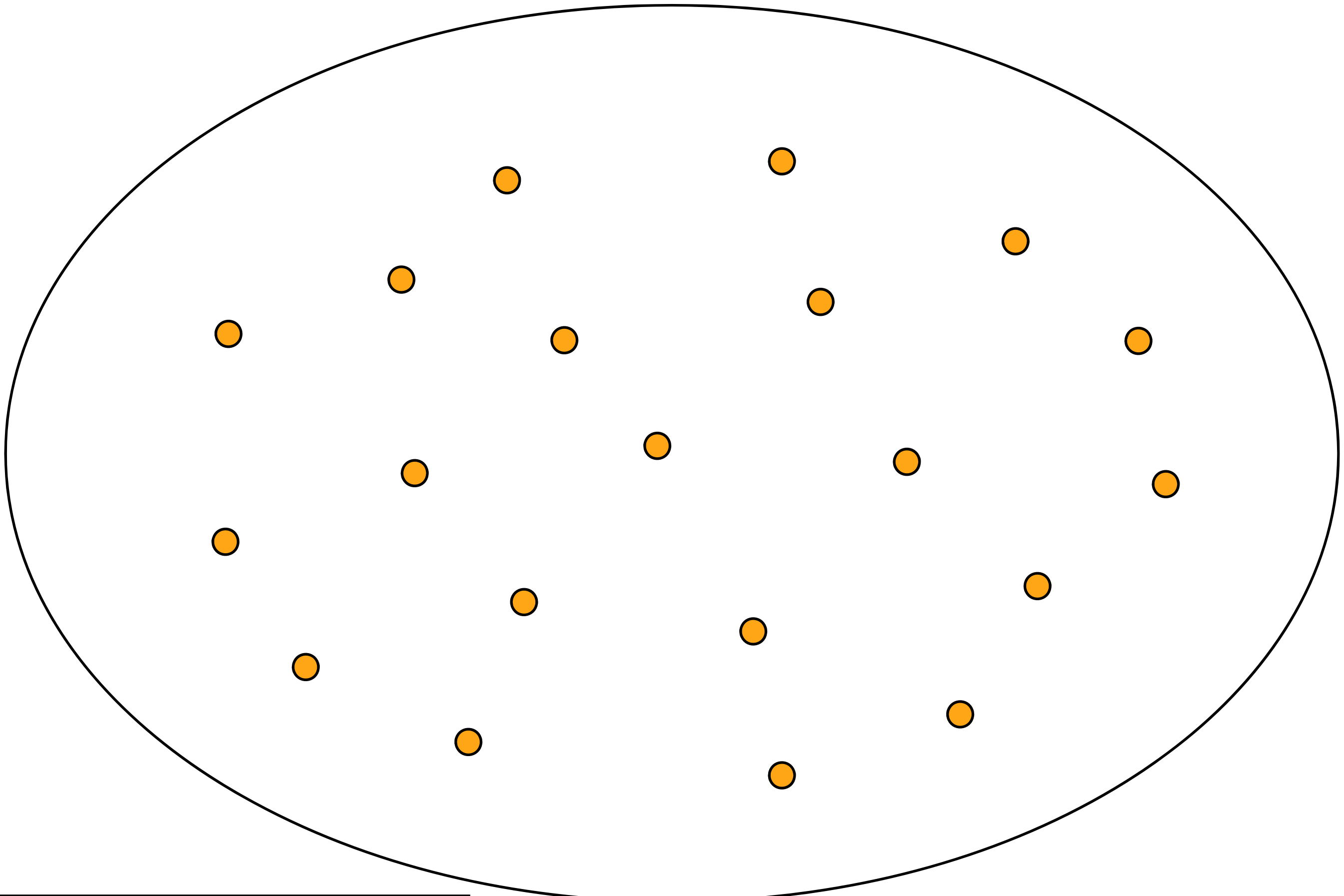
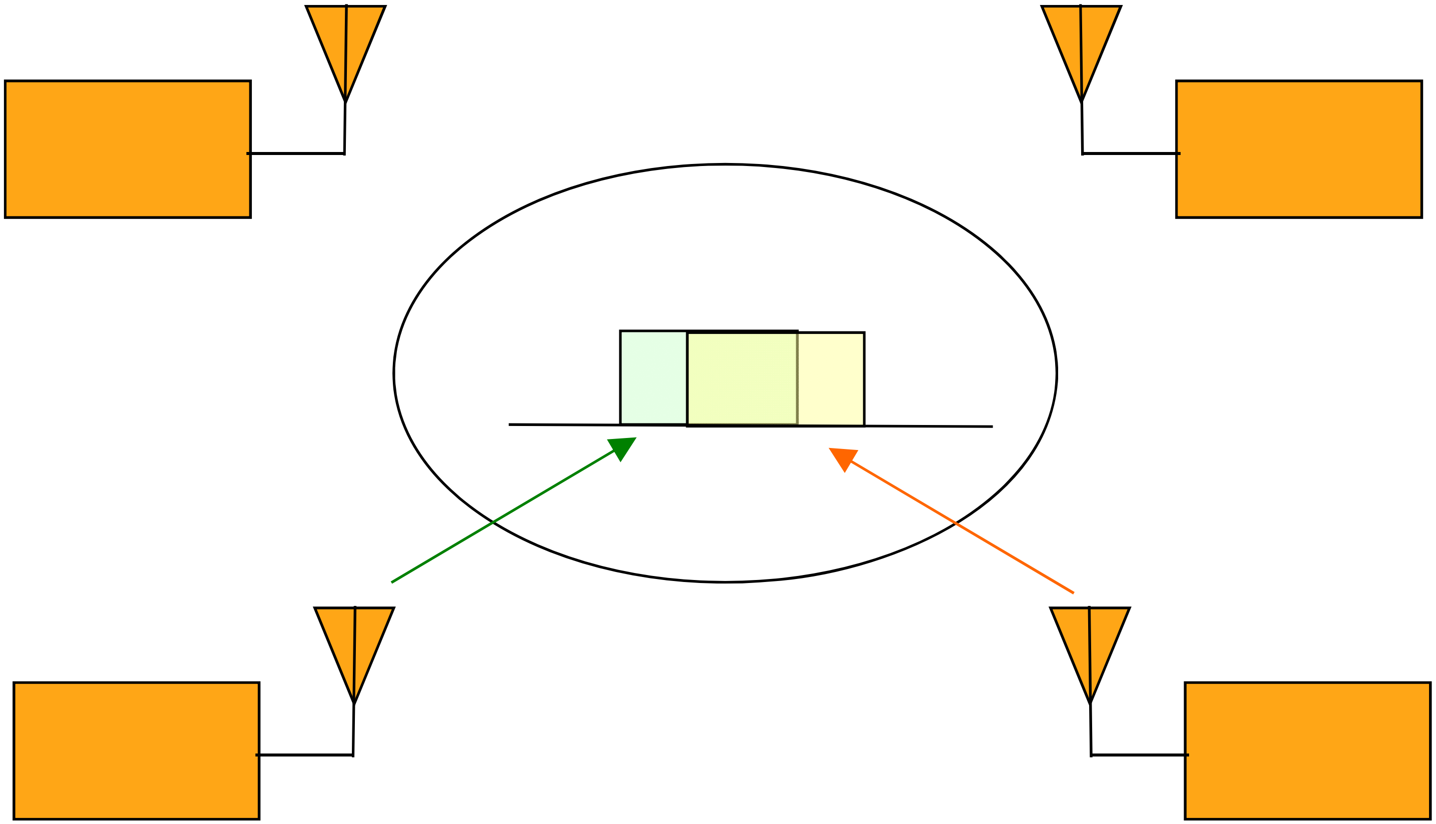
Fully Connected Network in the Reservation Channel



RTS & CTS use max. power.
Data & ACK are power adapted.

Packet Collision in Space



The question is how to maximize throughout while minimizing delay.

Arrival Statistics

We consider an N-node radio network, in which the network generates a total arrival rate of λ packets/sec. The probability of k arrivals in the time interval T, denoted by p(k) follows the Poisson distribution. Given the Poisson statistics, the mean and variance of arrivals are both λT. The time spacing between two successive arrivals, denoted by τ , is exponentially distributed with a probability density function of $f_\tau(\tau) = \lambda e^{-\lambda\tau}$ for $\tau \geq 0$. The probability between two successive events for a given time spacing τ decreases exponentially with τ .

The Probability of Collision-Free

In a slotted system the radio timing is synchronized, a vulnerable interval of two packets with packet lengths of m1 and m2 contenting the reservation channel equals to the larger of the two packet lengths, i.e., $Max(m_1,m_2)$, plus synchronization timing errors, and one-way propagation delay. Assuming the synchronization timing errors and the round-trip propagation delay of the radio's maximum range are negligible comparing to m_1 or m_2, the Probability of Collision-Free (P_{CF}) for a contention interval of $Max(m_1,m_2)$ seconds (i.e., no packets are overlapped during this time interval) can be shown as [1]:

$$P_{CF} = P_r[\notin Max(m_1, m_2)] = \int_{Max(m_1,m_2)}^{\infty} f_\tau(\tau)d\tau = e^{-[Max(m_1,m_2)\lambda]} \quad (1)$$

where $Max(m_1,m_2)$ represents the maximum value of m_1 and m_2. The Probability of Collision-Free (P_{CF}) is one the key traffic statistics that will be used for our analysis in this paper.

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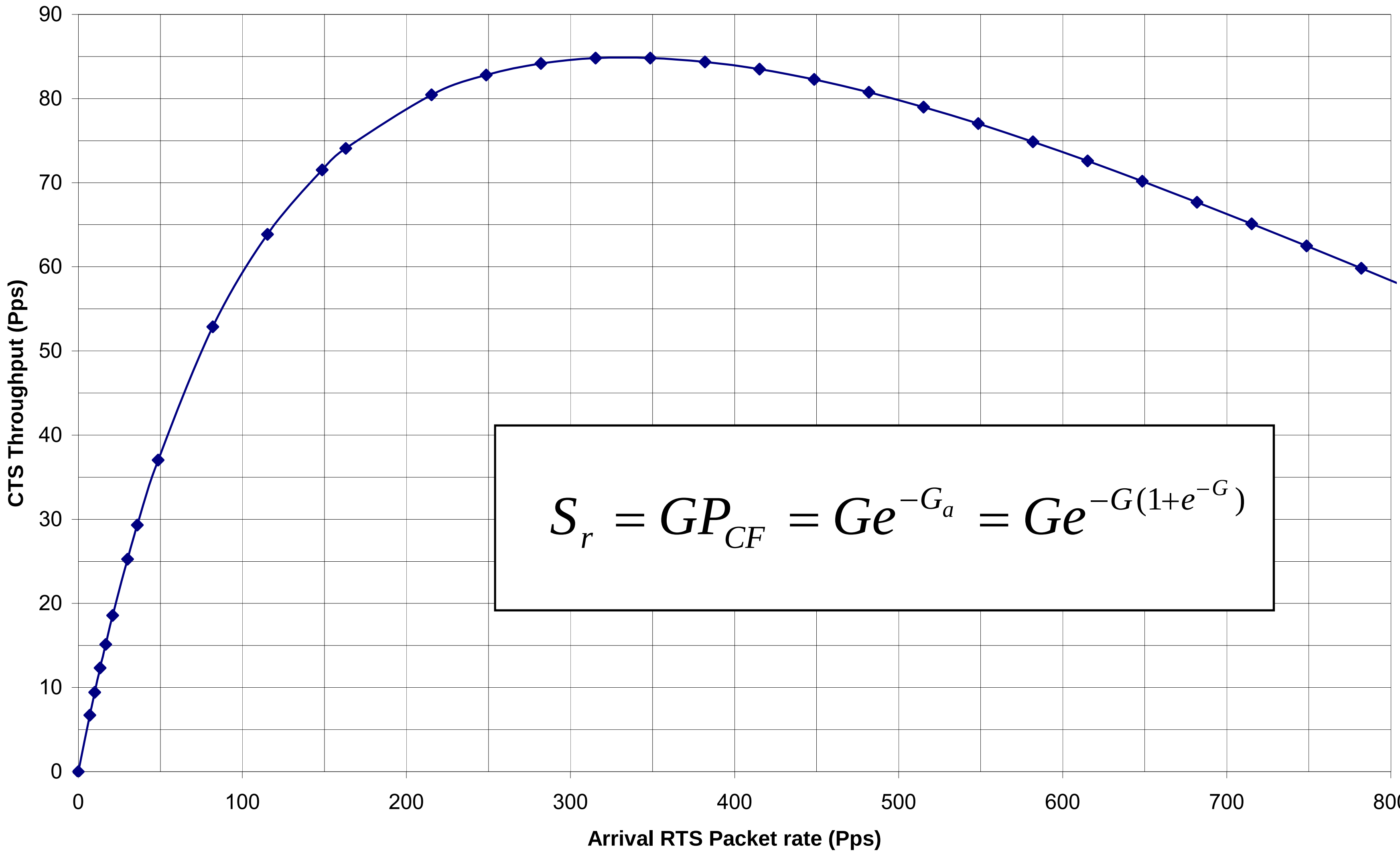
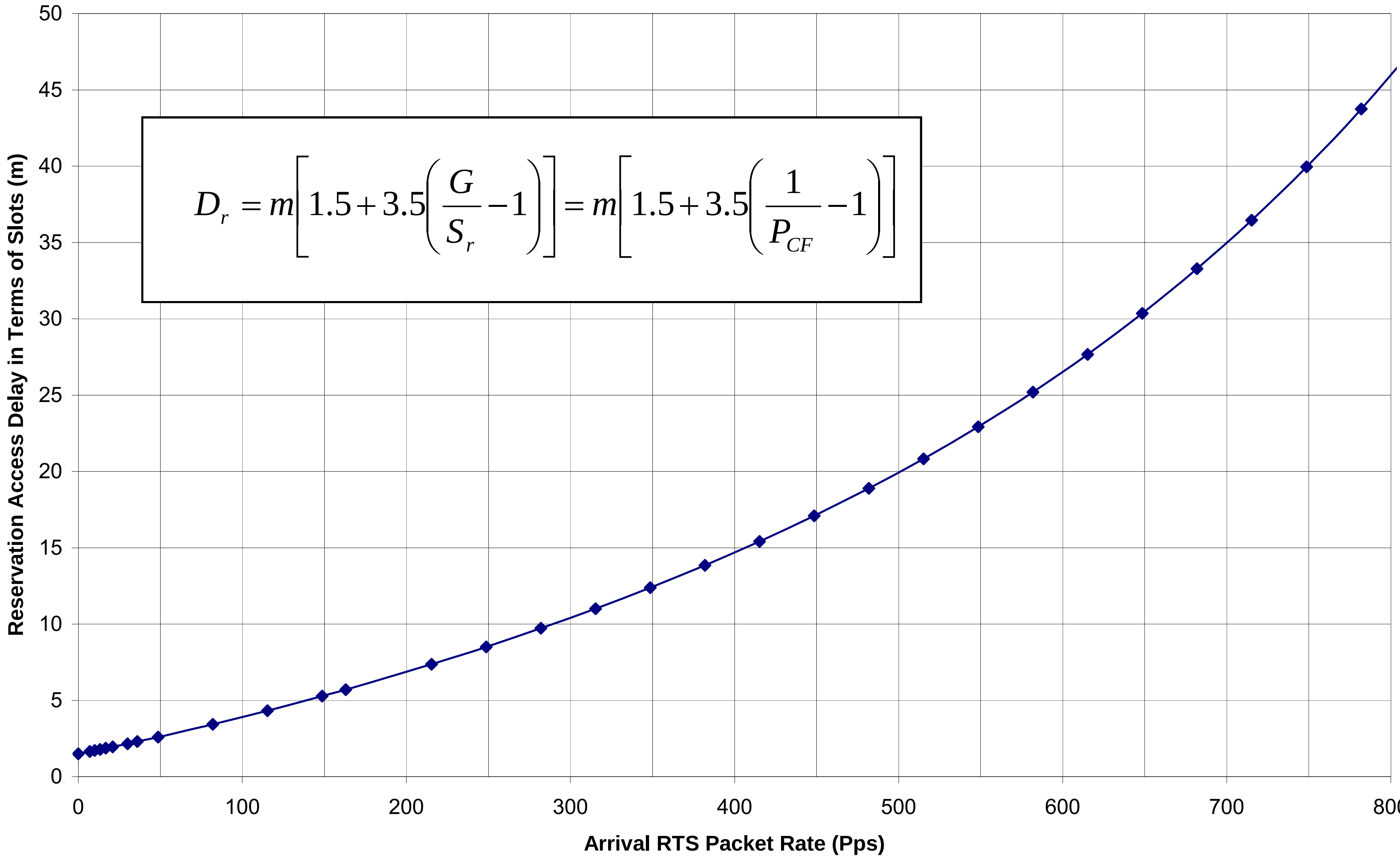
RTS Throughput Vs Arrival RTS Packet Rate



$$S_r = GP_{CF} = Ge^{-G_a} = Ge^{-G(1+e^{-G})}$$

Reservation Access Delay Vs Arrival RTS Packet rate



$$D_r = m\left[1.5 + 3.5\left(\frac{G}{S_r} - 1\right)\right] = m\left[1.5 + 3.5\left(\frac{1}{P_{CF}} - 1\right)\right]$$

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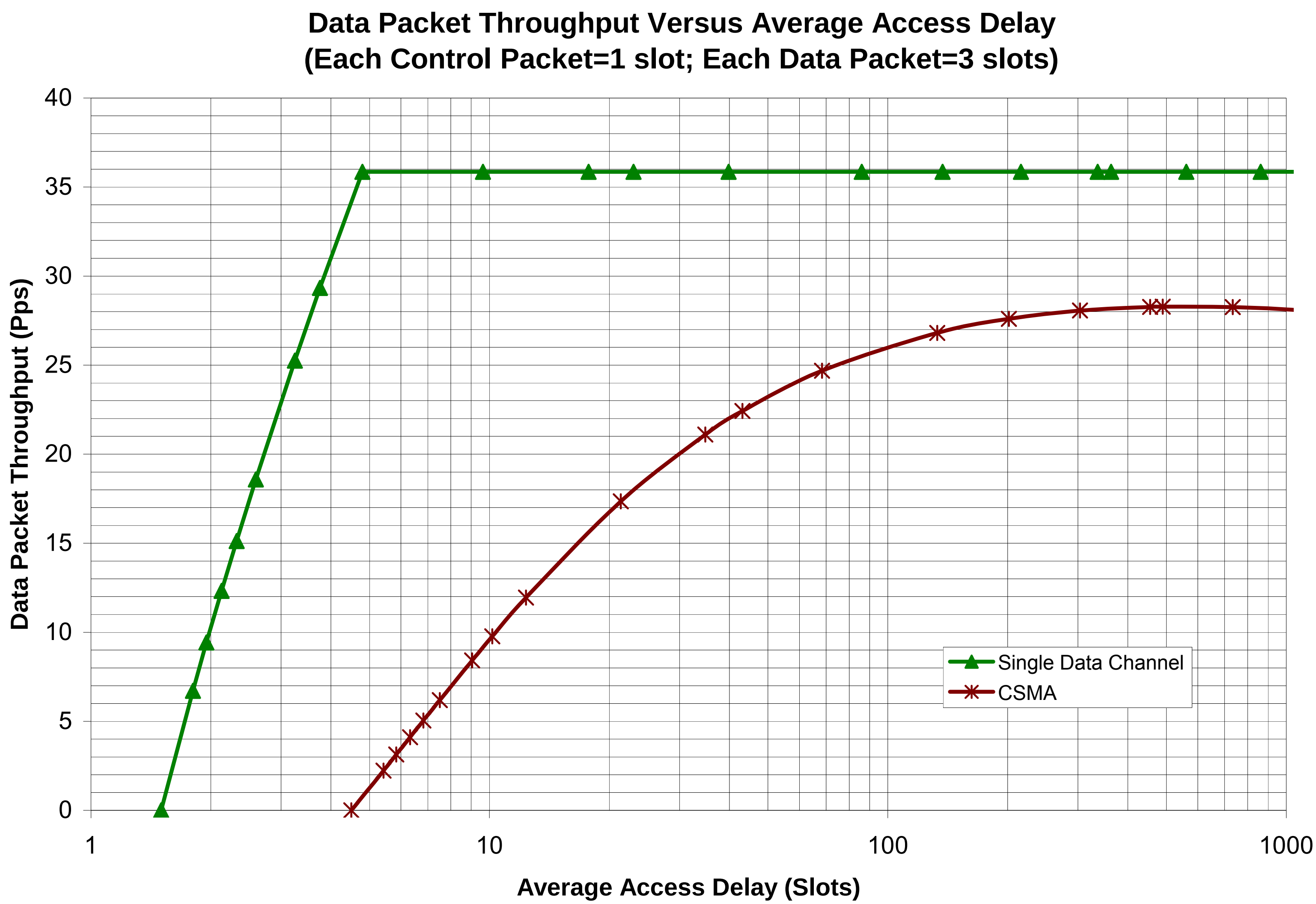
CSMA/CA_SD Performance

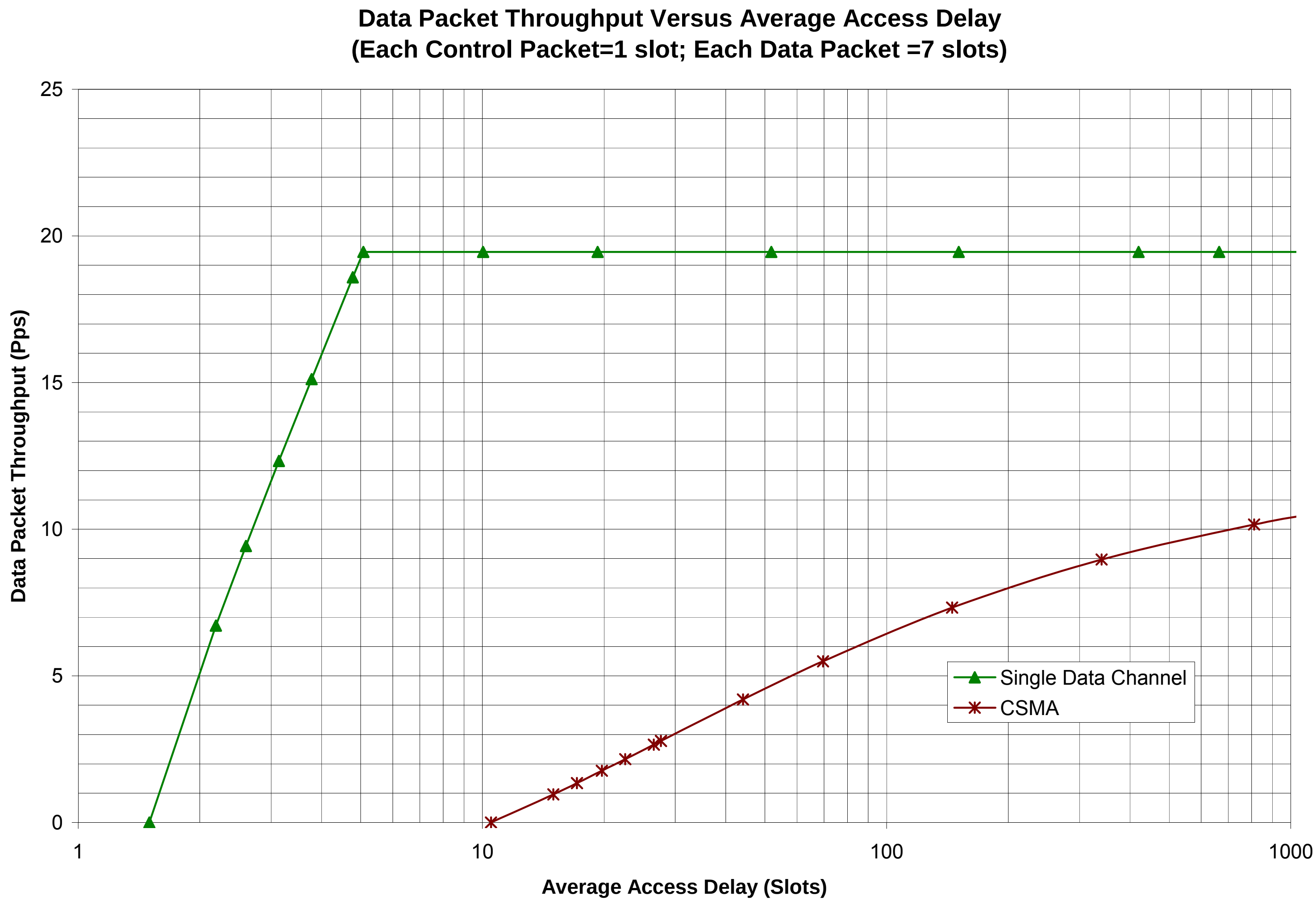
CSMA Versus CSMA/CA MAC Protocol

- One of the major problems of using pure CSMA in a wireless application is that it is not possible to listen while sending; therefore, collision detection is not possible. Since the collision probability is proportional to the packet length, the longer the data packet is, the worst is the throughput performance.
- Using the CSMA/CA protocol, radios compete to reserve the right to transmit a packet using relative short control packets, rather than directly competing for data transmissions using relatively long data packets in a CSMA based system.
- Thus, even for a single channel system, i.e., the CSMA/CA_SD, the data throughput and access delay characteristics should outperform that of a CSMA system.

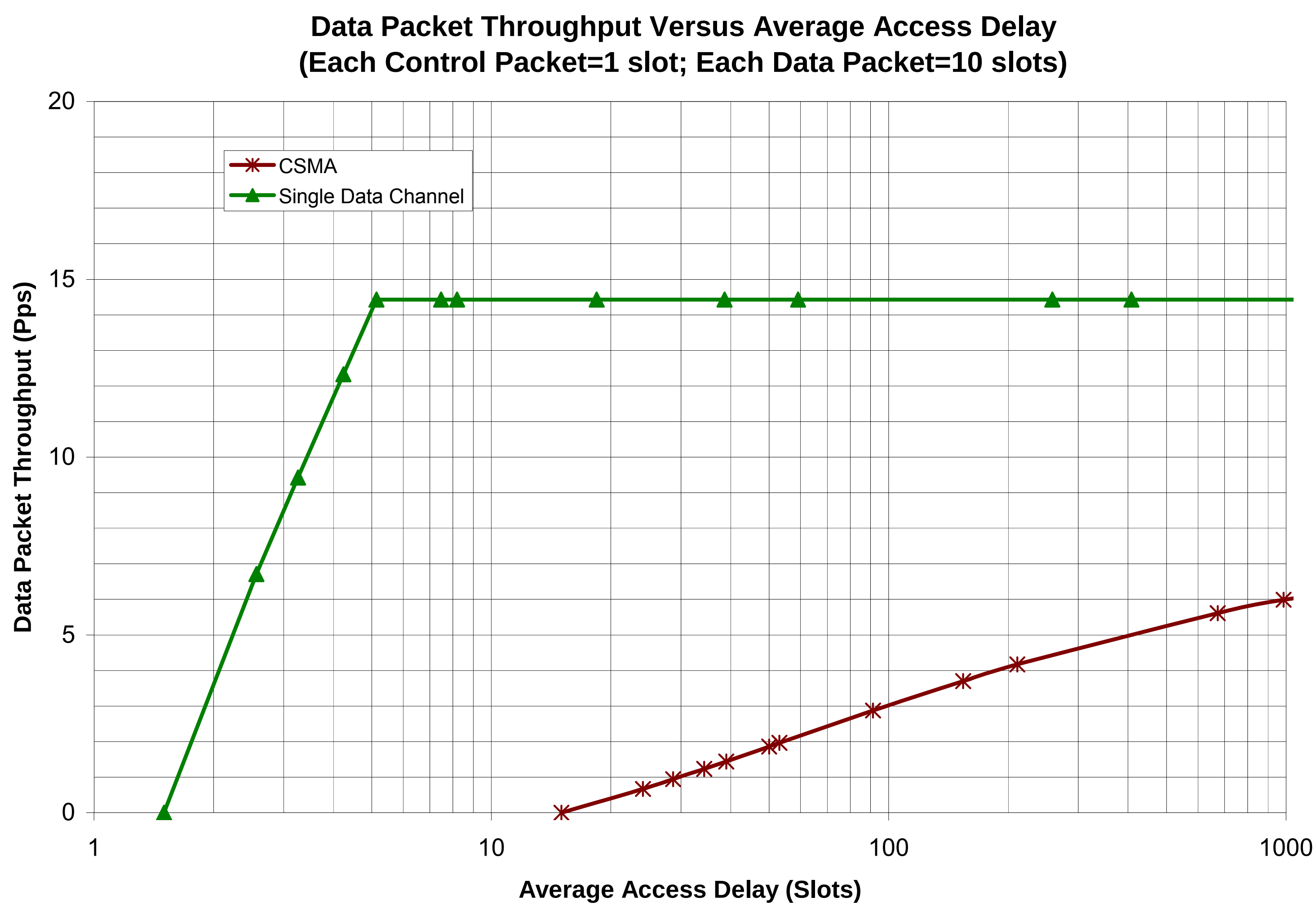
(a) Data/Control=3, CSMA/CA_SD versus CSMA



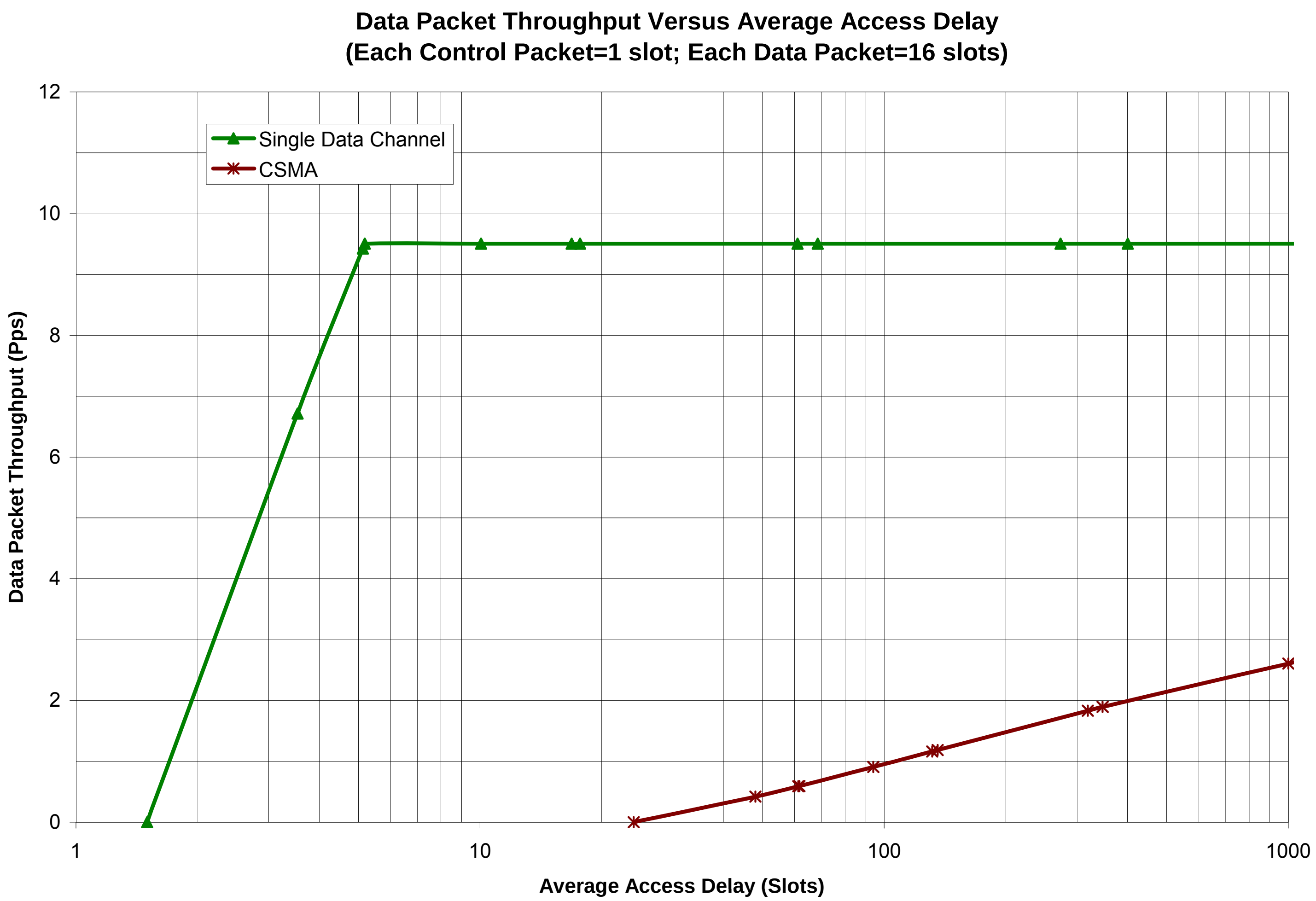
(b) Data/Control=7, CSMA/CA_SD versus CSMA



(a) Data/Control=10, CSMA/CA_SD versus CSMA



(b) Data/Control=16, CSMA/CA_SD versus CSMA



CSMA/CA_SD Versus CSMA

- The performance of CSMA/CA_SD is superior to that of CSMA in all cases, and
- The relative performance gain in terms of data throughput and access latency increases as the size of in larger data packets increases.

CSMA/CA_MD Access Delay Characteristics

Problem Formulation

- Assume the total number of channels for control access and data packets is *Nc*.
- Let each control access packet use 1 slot of the channel resource; i.e., $Lrts = Lcts = Lack = m = 1$ slot.
- Let each data packet uses *Ld* slots; Thus, the Data Throughput, denoted by *Sd*, can be written as

$$Sd = Sr*Ld = G*PCF*Ld$$

- However, the constraint $Nc \geq G + 2Sr + Sd$ must be met, because the total channel resource is bounded by *Nc*.

Delay Characteristics

- Using equation (5), the access delay for a RTS packet contending with a data packet can be written as

$$D_{d\_rts} = mL_d \left[1.5 + 3.5 \left(\frac{1}{P_{CF\_d}} - 1 \right) \right] \quad (6)$$

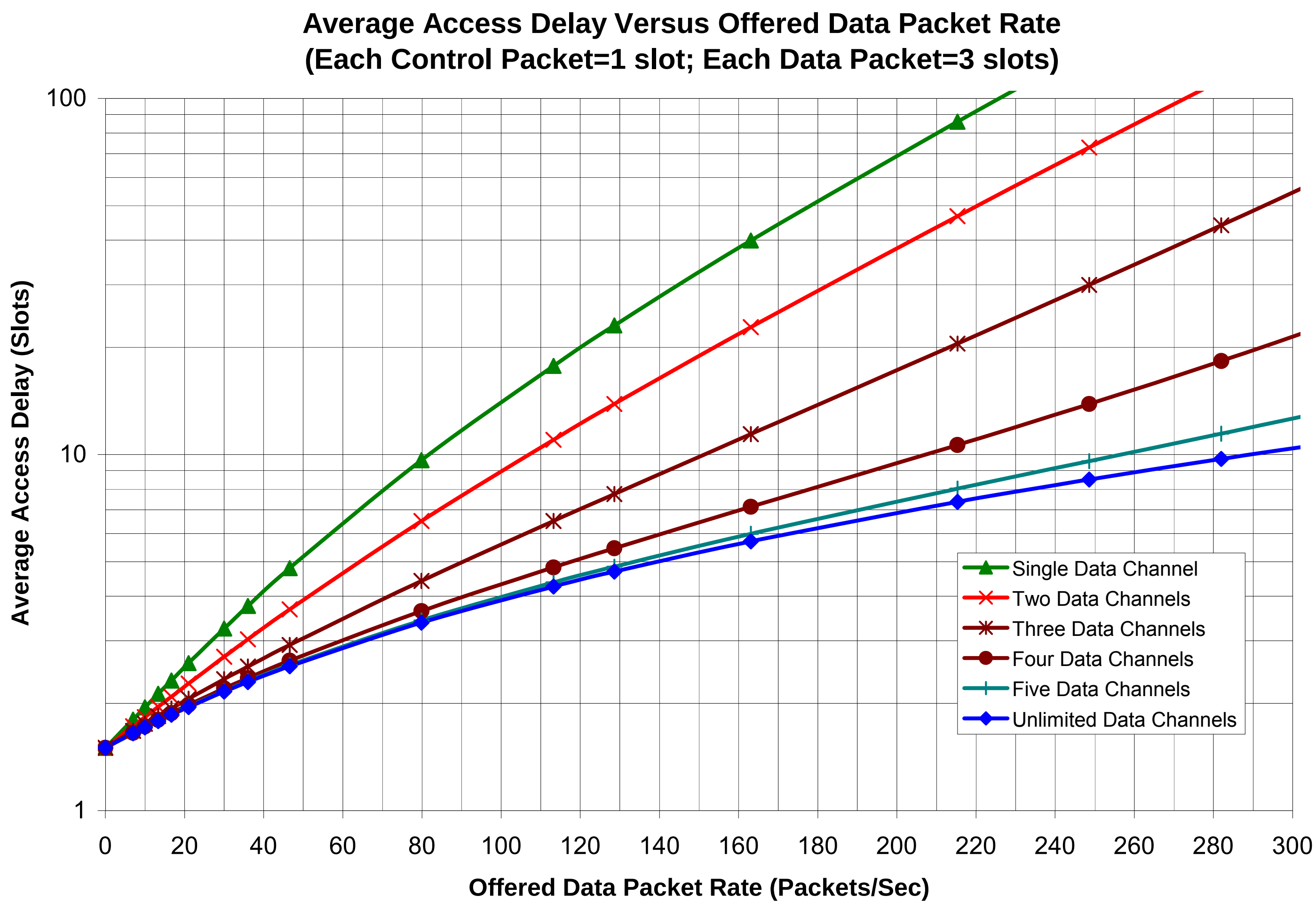
- Let *Nc* denote the total number of channels available. When *Nc*=1, the data shares the same channel as the reservation channel. The access delay of the single channel case can be shown as:

*D1= Dr*PCF*+(1- *PCF)* Dd_rts*

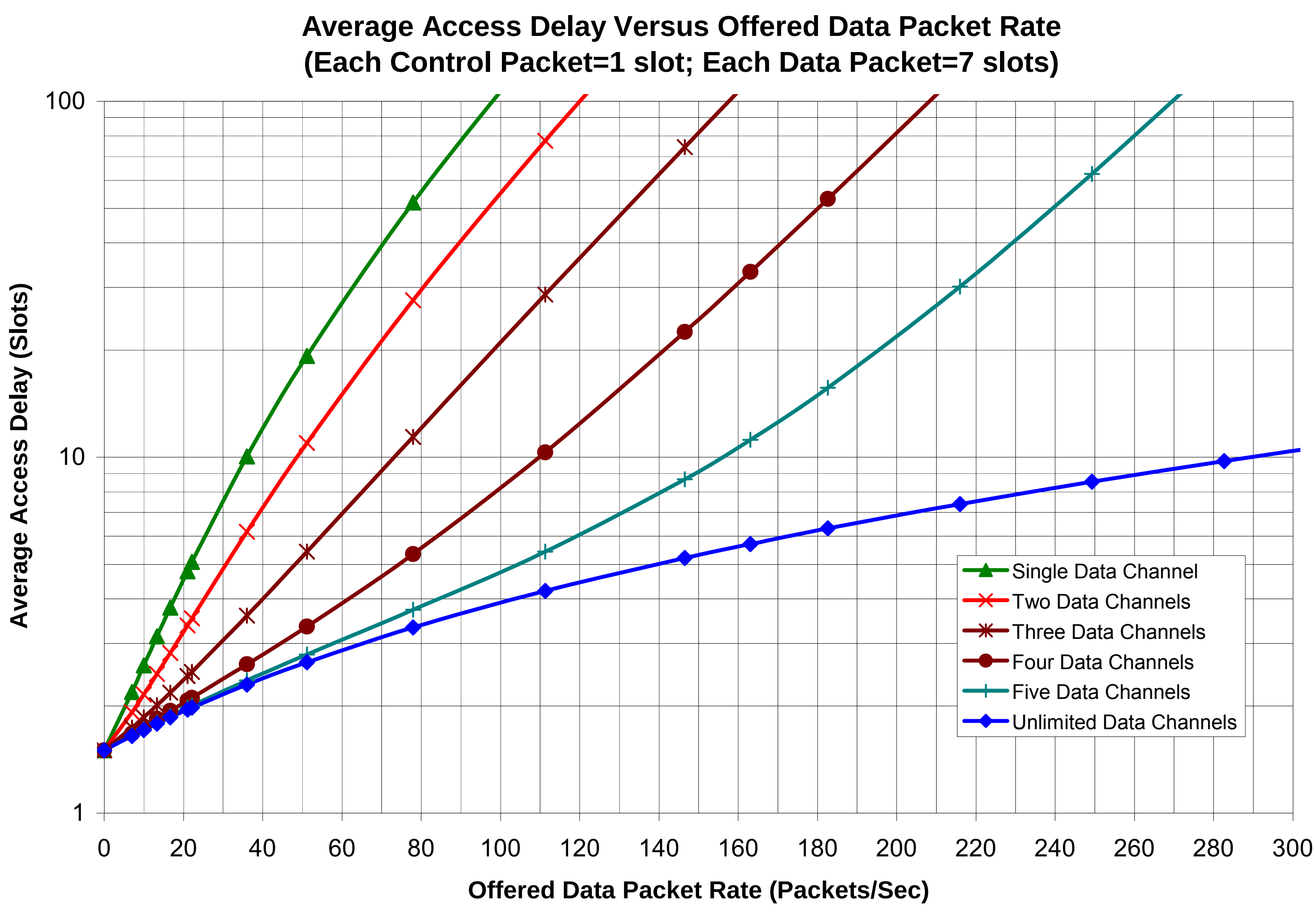
- The general expression for *Nc* ≥2 can be written as:

DNc =[(Nc -1) Dr+ Dn-1]/ Nc*

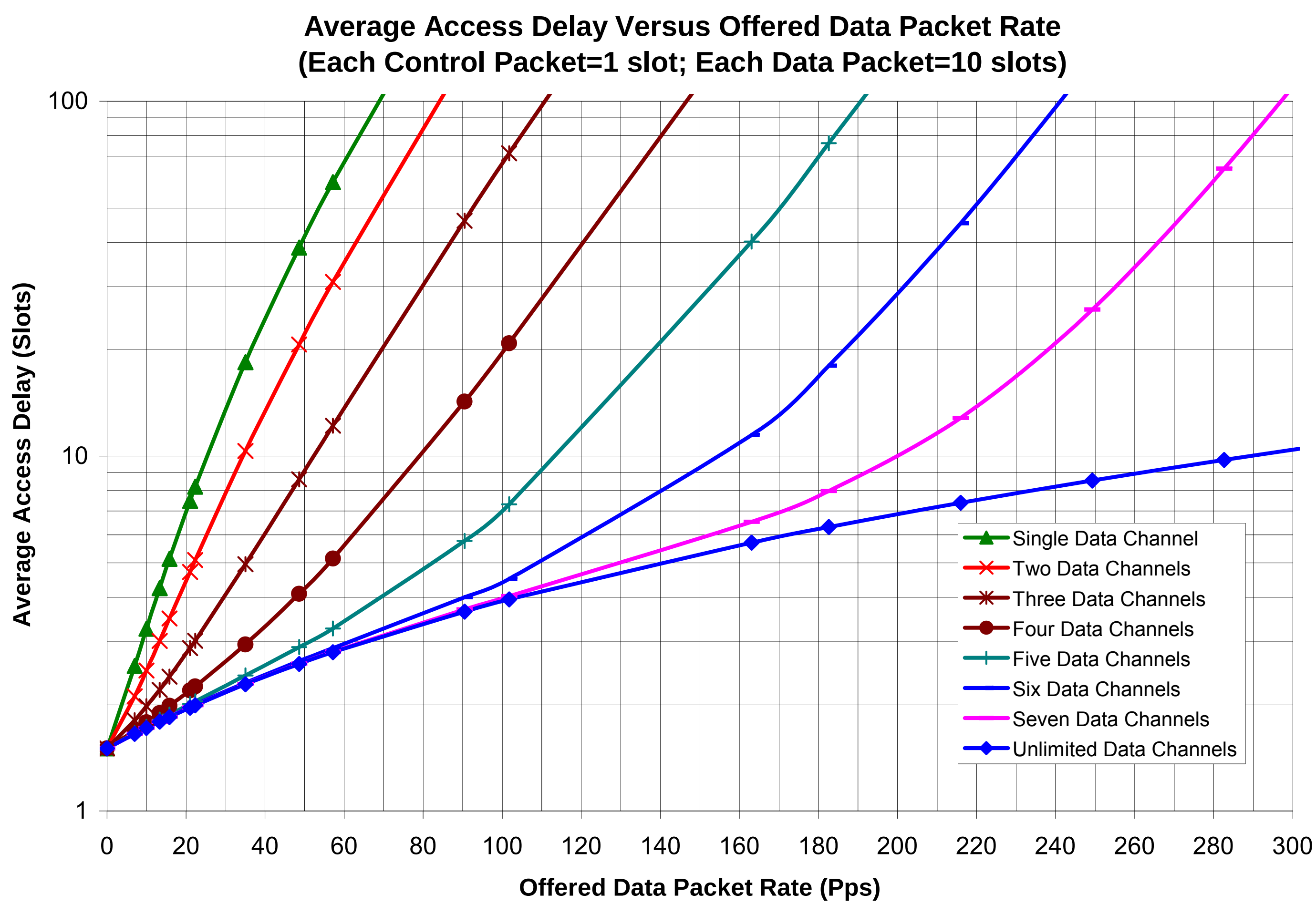
(a) Data/Control=3 Figure 3 – CSMA/CA_MD Access Delay



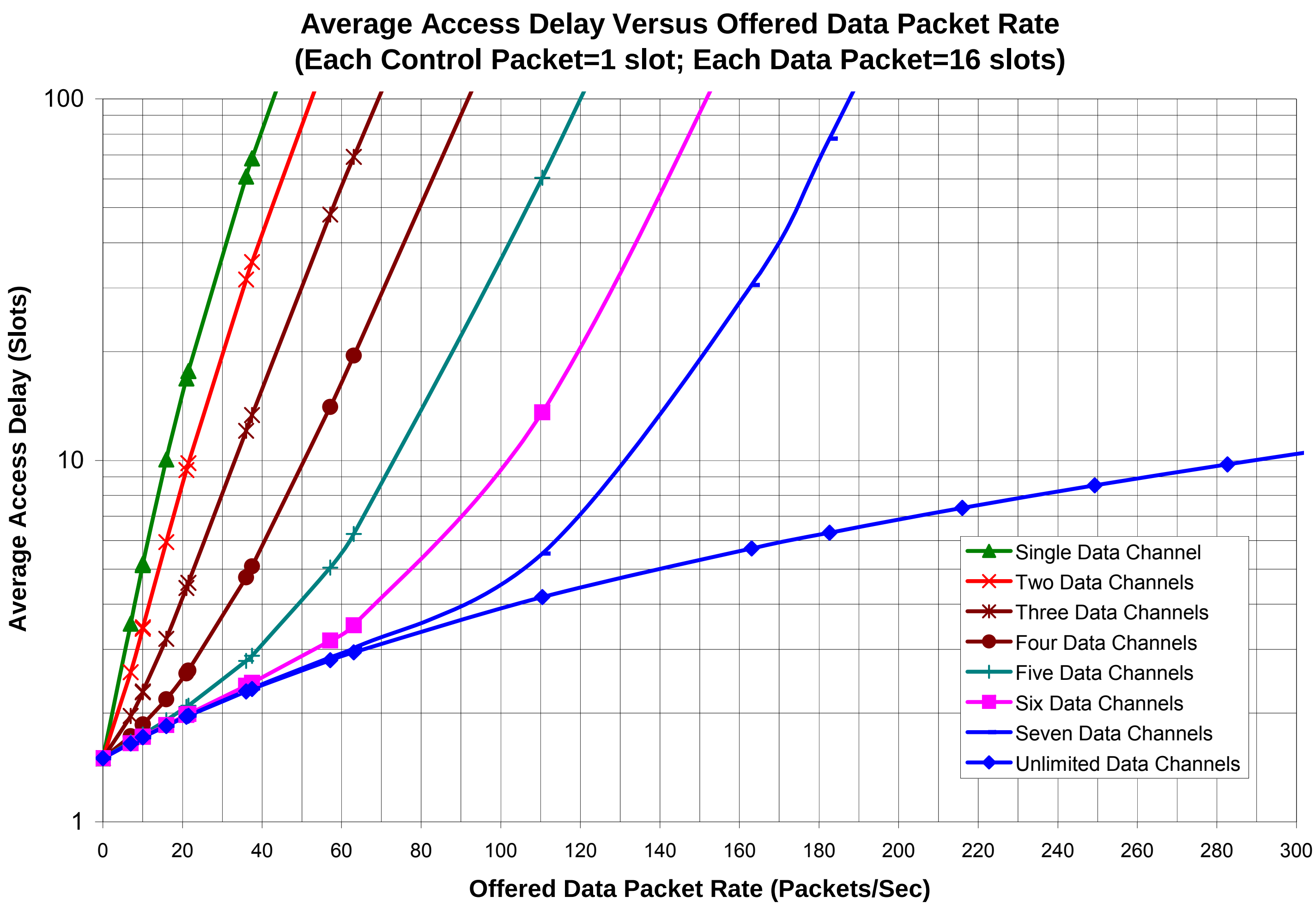
(b) Data/Control=7 Figure 3 – CSMA/CA_MD Access Delay



(a) Data/Control=10 Figure 4 – CSMA/CA_MD Access Delay

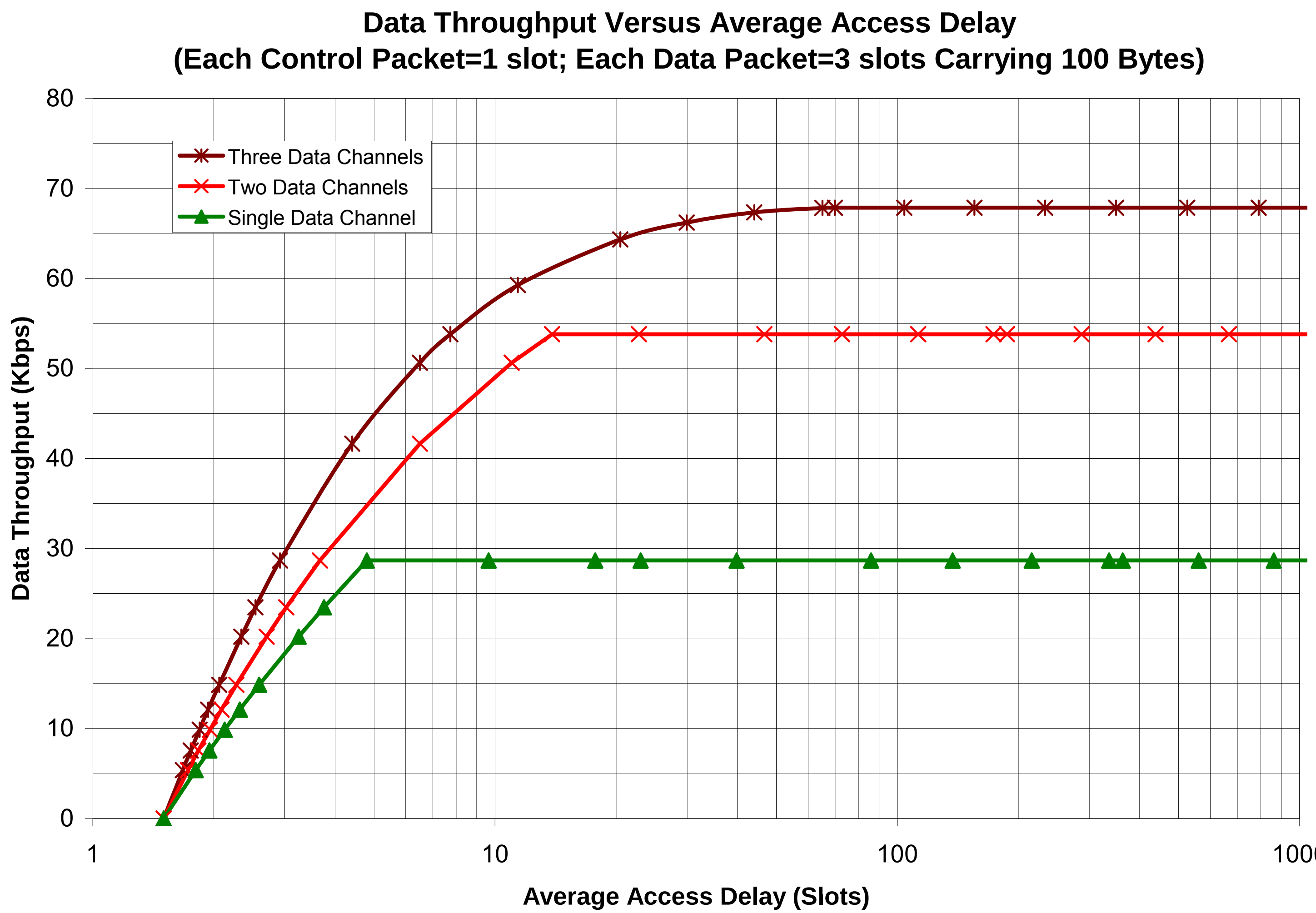


(b) Data/Control=16 Figure 4 – CSMA/CA_MD Access Delay

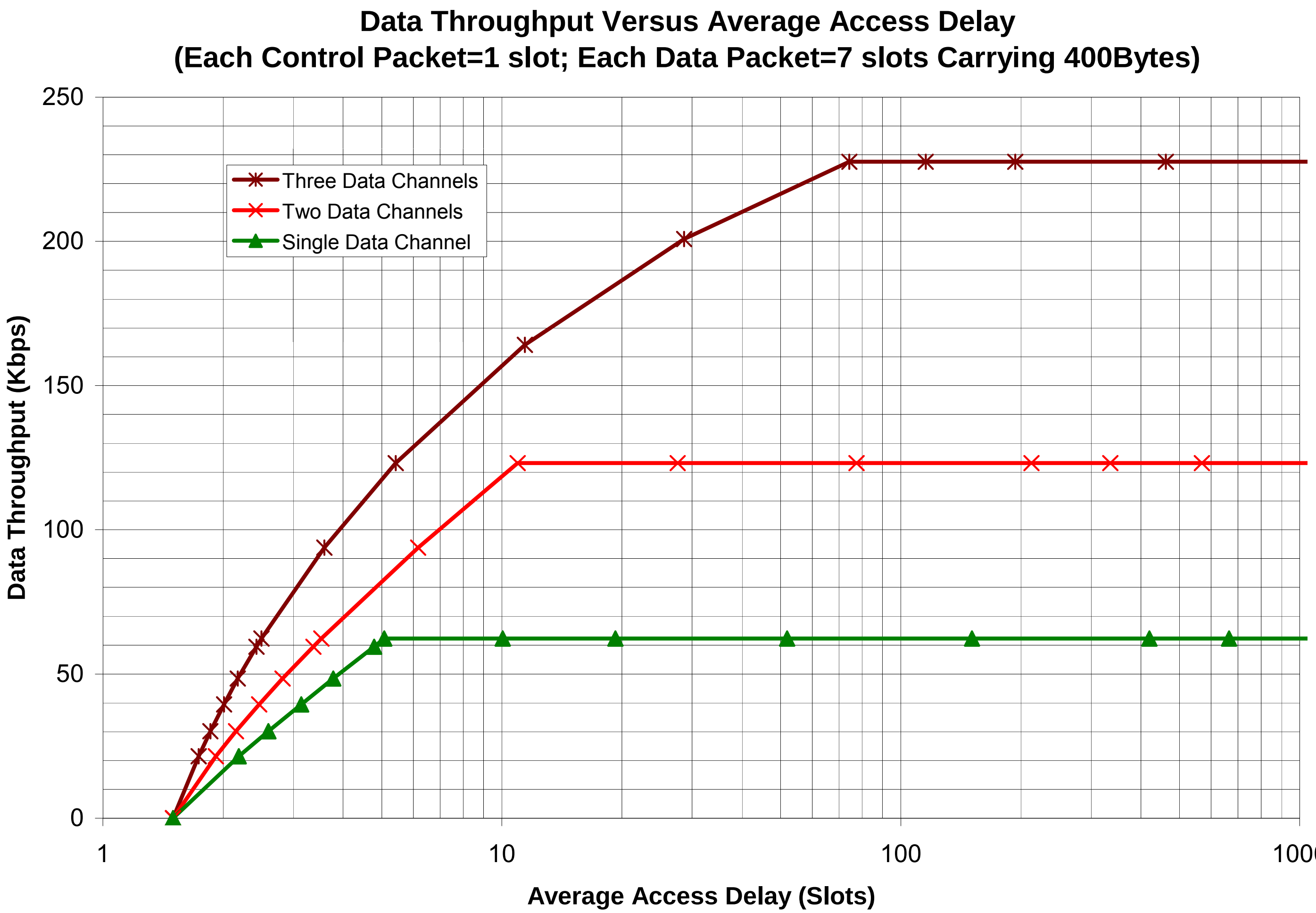


CSMA/CA_MD Operating Characteristics

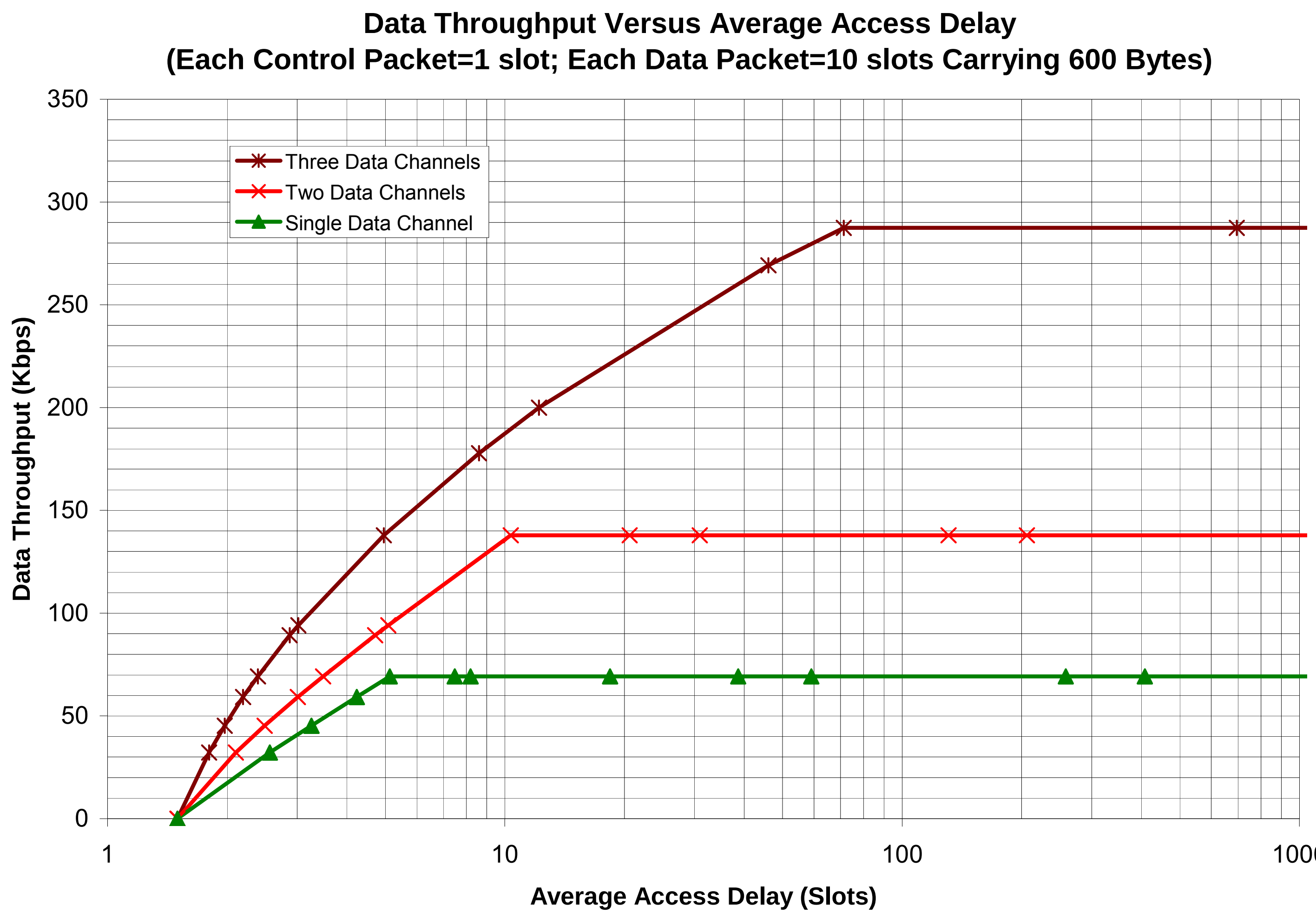
(a) Data/Control=3 Figure 5 – CSMA/CA_MD Data Throughput



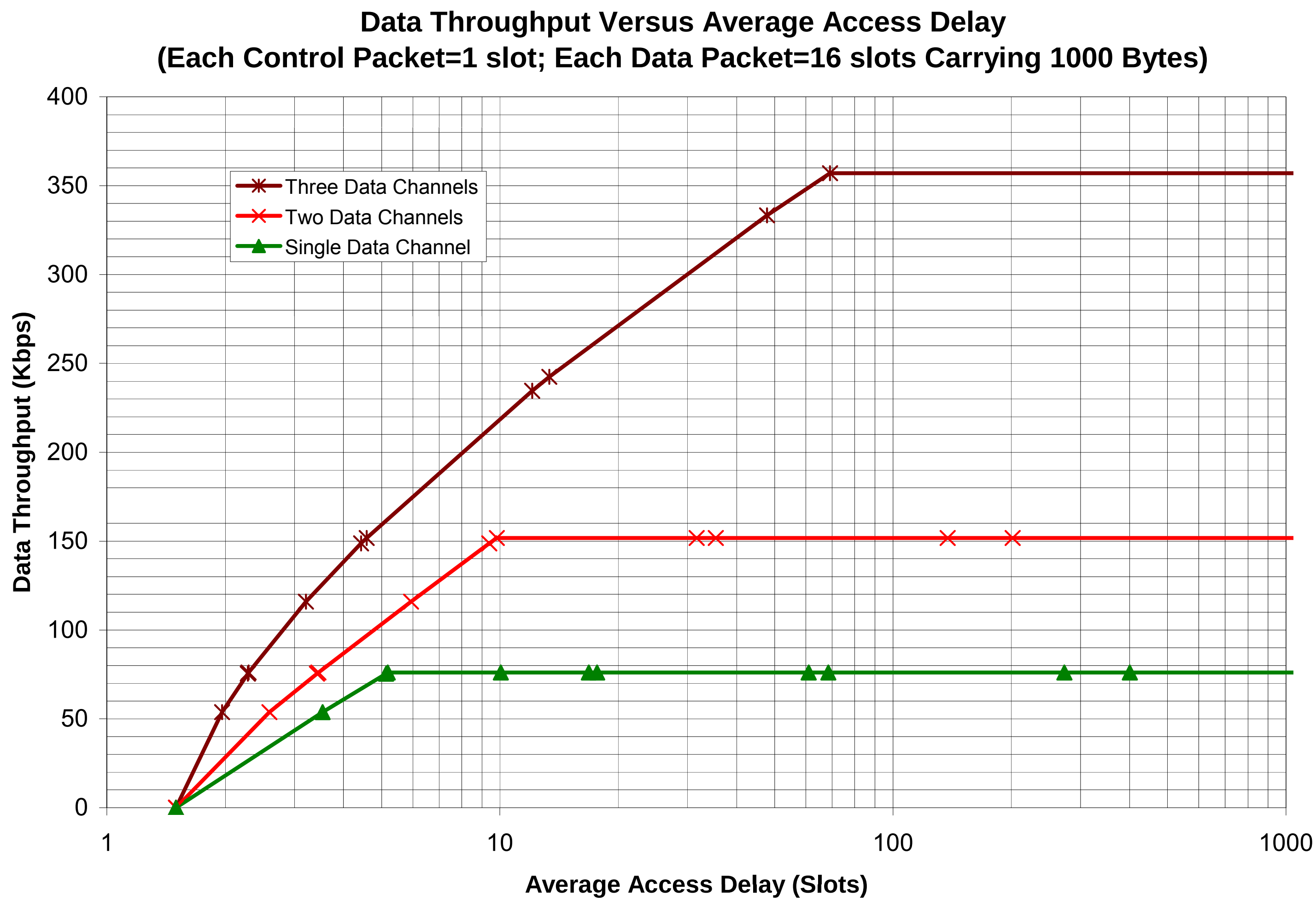
(b) Data/Control=7 Figure 5 – CSMA/CA_MD Data Throughput



(a) Data/Control=10 Figure 6 – CSMA/CA_MD Data Throughput



(b) Data/Control=16 Figure 6 – CSMA/CA_MD Data Throughput



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Concluding Remarks

- In this paper, we extend the CSMA/CA with a single data channel (CSMA/CA_SD) to the CSMA/CA with multiple data (MD) channels (CSMA/CA_MD).
- This paper derives the Operating Characteristics of CSMA/CA_MD, which provide a joint assessment of Data Throughput and Access Delay interoperated in varying network parameters and dynamics.
- The Operating Characteristics can easily be applied by users to assess the system performance achievable against their operational needs.
- The performance results indicate that the CSMA/CA_MD approach improves data performance, especially in the situation favoring spatial/spectral reuse with mixed data and bursty traffic conditions.
- The optimal number of data channels relative to a reservation channel may depend on the relative length of data packets compared to that of the control packets.

Reference

1) Mischa Schwartz, “Telecommunication Networks: Protocols, Modeling and Analysis,“ Addison Wesley, ISBN 0-2-1-16423-X

2) Ning H. Lu, “The Radio/Network architecture with the Enhanced Multiple Access Signaling,” ITT Working Paper WP-001101, 20 October 2004.