Distributed Channel Aware Link Scheduling for CSMA based Wireless Networks with Time-Varying Channels and Delay Sensitive Applications

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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In wireless networks, interference between neighboring links is an important issue. The link scheduling algorithm controls the interference between neighboring links such that no adjacent links can be concurrently active. Distributed throughput optimum algorithms for the link scheduling problem have been proposed in the literature. However, the maximum packet delays of these distributed throughput optimum algorithms can become arbitrarily large, which significantly degrades the performances of delay sensitive applications such as “Skype”. In this thesis, we propose two distributed link scheduling algorithms: a full opportunistic algorithm and a delay based adaptive algorithm. The proposed algorithms, while maintaining throughput optimality, increase the average delay performance of the previously proposed throughput optimum scheduling algorithms by 20% under the fading radio channel. We propose a new metric “Effective Goodput”, which measures the rate of packets that are successfully received before their respective playout times for delay sensitive applications. The delay based distributed adaptive scheduling algorithm proposed in the thesis increases the "Effective Goodput" by nearly 100% compared with the throughput optimum scheduling algorithms proposed in the literature.

Keywords: Wireless Networks, Distributed Link Scheduling, Delay Sensitive Applications, Fading, Effective Goodput

ÖZET

DAĞITIK VE KANAL BİLGİSİ KULLANAN, CSMA TABANLI KABLOSUZ AĞLARDA ZAMANLA DEĞİŞEN KANALLAR ALTINDA, GECİKMEYE HASSAS UYGULAMALAR İÇİN LİNK ÇİZELGELEME

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Kablosuz ağlarda, komşu linkler arasındaki etkileşim önemli bir konudur. Link çizelgeleme algoritması, komşu linkler aynı anda aktif olamayacak şekilde bu etkileşimi kontrol eder. Literatürede, link çizelgeleme problemi üzerine, çıktı optimalitesine sahip, dağıtık algoritmalar tasarlanmıştır. Ancak, bu algoritmalardaki maksimum paket gecikme değeri yüksek olabilir ve bu durum “Skype” gibi gecikmeye hassas uygulamalarda performansın önemli seviyede düşmesine neden olur. Bu tezde, iki dağıtık link çizelgeleme algoritması tasarlanmıştır: tam opportünist algoritma ve gecikme tabanlı adaptif algoritma. Tasarlanan algoritmalar, çıktı optimalitesine sahip olup, daha önceden tasarlanmış çıktı optimalitesine sahip çizelgeleme algoritmalarının ortalama gecikme performanslarını sönümlemeli radyo kanallarında 20% oranında arttırmıştır. Ayrıca, gecikmeye hassas uygulamalar için zamanaşımına uğramadan başarılı bir şekilde paketlerin alınmasının oranını ölçen “Etkili Başarılı Çıktı” tanımlanmıştır. Bu tezde tasarlanan gecikme tabanlı dağıtık adaptif çizelgeleme algoritması, literatürdeki çıktı optimalitesine sahip algoritmalarla karşılaştırıldığında, “Etkili Başarılı Çıktı” göz önüne alındığında, yaklaşık olarak 100% performans artışı sağlamıştır.

Anahtar Kelimeler: Kablosuz Ağlar, Dağıtık Link Çizelgeleme, Gecikmeye Hassas Uygulamalar, Sönümleme, Etkili Başarılı Çıktı

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To My Father ...

Chapter 1

Introduction

With increasing demand in today's mobile technologies, wired applications are replaced by wireless technologies. Wireless technologies enable more efficient and more user friendly applications that ease our lives. Thanks to these wireless technologies, today, applications on file sharing, mobile telecommunication, sensor networks, radio and satellite transmission, internet and various other areas are possible. Due to the popularity of wireless applications and inherent problems of propagation in the wireless environment such as noise and interference, wireless networking has been a very important research area in the last decades.

Due to this rapid growth of wireless technologies for commercial and military applications, the radio spectrum is getting full, which remains no space for the upcoming technologies. In order to supply good quality-of-service (QoS) in the technologies, scheduling of the wireless links subject to interference constraints has become an important research area, which is the main focus of this thesis.

Since spectrum is getting full, new technologies will have to co-operate with other technologies that use the same frequency band, which will increase the interference among transmissions. Unlike wired technologies, in wireless medium, signals used for transmission in one link can also be heard by the receivers and transmitters nearby, which affects the transmission on the links that are close. Signals on the transmitter sides and receiver sides collide with each other if they are carried on the same frequency band, making a successful reception at the receivers more difficult. One simple principle in order to reduce interference is that no interfering links should have concurrent transmissions. Since links that are close to each other create more interference, when compared to the links apart from each other, the degree of interference should be specified. In this idea, if interference between two links is larger than some pre-specified threshold, those links are assumed to be "neighbors" and links that are neighbor to each other should not have transmissions simultaneously. Thus, *link scheduling algorithm* decides which of the links in the wireless network should transmit at a given time instant such that transmitting links at that time will not interfere with each other and the radio spectrum is efficiently utilized [1], [2].

Different types of scheduling algorithms have been proposed. First, centralized solutions have been proposed where the main concern is the throughput optimality, meaning that network queues do not grow to infinity for all arrival rates in the capacity region of the network. Queue-length based "Maximum Weighted Scheduling (MWS)" algorithm is one of the centralized solutions to the link scheduling problem [5]. In MWS, links are associated with weights and the non-interfering link combination with maximum sum of weights is selected as the schedule [5]. Weights may be selected as simply the queue-lengths of the links. MWS is proven to be throughput optimum [5]. The problem with MWS is that it is centralized and for general topologies, the solution becomes an NP-Hard problem.

“Maximal Scheduling” is another solution to the link scheduling problem, where it stabilizes the network for some arrival rates in the capacity region [6], [7]. “Greedy Maximal Scheduling (GMS)”, which is also interpreted as the “Longest-Queue-First (LQF) Scheduling” is another alternative link scheduling algorithm, which is less complex. In GMS, in a sequential order, the link with maximum queue-length is scheduled and its interfering links are deactivated. In [8], GMS is proven to be throughput optimum if the network satisfies the “local-pooling” condition. However, for general networks GMS cannot keep the network stable even for arrival rates in the capacity region [9], [10], [11].

Link scheduling algorithms which are CSMA (Carrier Sense Multiple Access) based random access algorithms have also been proposed. In CSMA, the sender first senses the channel, and if there is no ongoing transmission in the medium, it transmits the packet. If the sender senses an ongoing transmission in the channel, it waits for a random back-off time and senses the channel again. Since CSMA-type algorithms can be designed in a distributed way, they are practical. In [12], a mathematical model is introduced in order to compute the throughput of a CSMA-type algorithm in wireless networks and it is shown that Markov chain representing the transition between transmission schedules obtained by the algorithm has a simple product form stationary distribution assuming no propagation delays and no occurrances of collisions. In [13], this model is used for the throughput analysis in wireless networks. According to the results presented in [12], [13], a distributed algorithm is proposed for choosing the CSMA parameters for unknown arrival rates [14]. In [15], based on the results in [14], [16], [17] and [18], a CSMA based throughput optimum scheduling algorithm is presented. In [15], link weights are assumed to be a function of queue-lengths, which is a modified version of MWS where link weights are simply the queue-lengths. In addition, it is also assumed that the maximum queue-length information is distributed into the network via message sharing between links.

Hybrid Q-CSMA scheduling [1] brings important contributions to earlier studies in [12], [14], [15], [19], [20], [21], [22]. Hybrid Q-CSMA algorithm is a distributed scheduling algorithm which uses both the benefits of GMS and CSMA type algorithms. According to the results presented for the CSMA type algorithms, even though they are throughput optimum, their delay performance is worse than MWS and GMS. However, Hybrid Q-CSMA algorithm combines the benefits of all these algorithms and improves the delay performance. Furthermore, in Hybrid Q-CSMA algorithm, schedules consisting of non-interfering links are presented even though packet collisions are possible in the control phase, which is different from idealized CSMA assumptions in [12], [14], [15]. In this thesis, Hybrid Q-CSMA Scheduling is extended.

The algorithms proposed for the link scheduling problem assume that the wireless medium is ideal, where there is no transmission error. However, in real life, packet losses are frequently observed in wireless communication, according to "small scale fading" caused by the multi-paths and Non-line-of-Sight propagation environment (NLOS). Since all the upcoming technologies require mobility, the channels of the links will be time-dependent so fading should be considered by the scheduling algorithms.

In addition, as a performance metric in these algorithms, throughput is considered but the delay is not considered. However, in interactive applications such as “Skype”, packets delivered after the scheduled playout time are useless. This issue becomes more crucial in the case of fading, since decrease in the data rates of the links under fading results in an increased packet delay.

Since the need for wireless applications is increasing and spectrum usage is becoming a problem, distributed scheduling algorithms become more important. In addition, the performances of the algorithms under realistic environment models have not been tested for fading cases and the delay performance of these algorithms has not been studied. Since the usage of scheduling algorithms will be more crucial in the future when wireless links will be deployed more densely, improvements on the scheduling algorithms for real-life scenarios are necessary, which is the main motivation of this thesis.

In this thesis, we consider a more realistic model for the wireless environment. Today, adaptive modulation and coding (AMC) scheme is used widely, where the modulation type and the coding rate used in communication are changed according to the Bit Error Rates (BER) to improve the efficiency in data transmissions. BER in the environment changes through time due to fading and mobility. For better characterization of the radio environment, AMC profiles supported by IEEE 802.16 standards have been examined. From the supported AMC profiles, we have selected four burst profiles: 64-QAM $\frac{2}{3}$, 16-QAM $\frac{1}{2}$, QPSK $\frac{1}{2}$ and BPSK $\frac{1}{2}$. Although the number of burst profiles supported by the standards is much larger, we considered only four profiles for simplicity. When the AMC profile uses smaller modulation constellations, BER decreases for a given Signal-to-Noise ratio (SNR). However, as a drawback, the spectral efficiency and the data rates decrease. The spectral efficiencies of the profiles 64-QAM $\frac{2}{3}$, 16-QAM $\frac{1}{2}$, QPSK $\frac{1}{2}$ and BPSK $\frac{1}{2}$ are 4, 2, 1 and 0.5 b/s/Hz, respectively.

We assume that fading durations are exponentially distributed. We model the fading process by a 4-state Continuous Time Markov Chain (CTMC), where each state corresponds to a range of fading depths suitable for supporting each AMC profile. As the channel model, Stanford University Interim (SUI) channel model [23] is used. The transition rates of the 4-state CTMC have been determined according to Bit Error Rate (BER) vs. SNR plots and Spectral Efficiency vs. SNR plots for these 4 different burst profiles in SUI channels [3]. In addition, research on Level Crossing Rates (LCR) and Average Duration of Fades (ADF) for SUI channel models, has also been used in the determination of the transition rates of the CTMC-based fading model.

We use the Hybrid Q-CSMA algorithm as the starting point for the link scheduling algorithms proposed in this thesis. Two different channel state aware approaches are implemented to improve the performance of Hybrid Q-CSMA algorithm under time-varying fading radio channels. First algorithm is the "Full-Opportunistic Algorithm", where each link is assumed to know the burst profiles used in its neighboring links. This assumption is possible in the nature of Hybrid Q-CSMA algorithm, since there is a packet exchange mechanism for the identification of the neighboring links. As a result, burst profile information can also be encoded in these packets. In the "Full-Opportunistic Algorithm", link chosen for transmission by Hybrid Q-CSMA algorithm, checks the fading conditions of its neighbors. If their channel states are in better condition, transmission in the chosen link is avoided to provide transmission opportunity for its neighboring links.

This is because data rates in those links are higher, which increases the spectral efficiency of the network. As an improved version of the "Full-Opportunistic Algorithm", "Delay Based Adaptive Algorithm" is presented where maximum delay is also considered. We assume that there is a pre-defined delay threshold where packets that experience a delay exceeding this threshold are lost. In the "Delay Based Adaptive Algorithm", link chosen for transmission by the Hybrid Q-CSMA algorithm, checks the fading conditions of its neighbors. In addition, the probability of packet loss due to timeout is estimated by a simple threshold check. If the packets in the link are likely to be transmitted successfully before their respective timeouts and the conditions of the neighbors are better, transmission is avoided, to increase the spectral efficiency in the network. However, if the packets waiting in the buffer are likely to be lost due to timeout violation, link is given transmission opportunity to prevent packet losses so that Hybrid Q-CSMA is applied. This scheme provides improvement in the delay performance when compared with the "Full Opportunistic Algorithm". Furthermore, in the "Delay Based Adaptive Algorithm", packets that have already exceeded their respective playout time for successful delivery are not transmitted to increase the spectral efficiency.

Under time-varying fading radio channels, the performances of the proposed approaches have been compared in terms of average queue-length, probability of reception before timeout and "Effective Goodput" which is simply the multiplication of arrival rate and probability of reception before timeout for different topologies. As a result, both "Full Opportunistic Algorithm" and "Delay Based Adaptive Algorithm" significantly improve the performance of Hybrid Q-CSMA algorithm. According to the results, average queue-length performance of Hybrid Q-CSMA algorithm is improved by about 10% to 20% by the "Full Opportunistic Algorithm" and "Delay Based Adaptive Algorithm", respectively. Performance improvements in the probability of reception before timeout and "Effective Goodput" are more substantial: up to 75% and 100% performance improvements in terms of "Effective Goodput" are obtained by the "Full Opportunistic Algorithm" and "Delay Based Adaptive Algorithm", respectively.

The rest of the thesis is organized as follows. In Chapter 2, the network model for the scheduling algorithms is presented first. Furthermore, the basic scheduling algorithm is presented and its throughput-optimality is discussed. A distributed version of the basic scheduling algorithm (Q-CSMA) and its improved version Hybrid Q-CSMA algorithms are presented and their average delay performances are presented under the ideal radio channel model.

In Chapter 3, the adaptive modulation/coding (AMC) scheme is presented. Furthermore, the effect of "small scale fading" is examined and a Continouos Time Markov Chain (CTMC) model for the operation of AMC under the fading radio channel is introduced. The state transition rates of the CTMC are determined according to Level Crossing Rates (LCR) and Average Duration of Fades (ADF) statistics provided by the SUI model.

In Chapter 4, performances of the proposed "Full Opportunistic Algorithm" and "Delay Based Adaptive Scheduling Algorithm" under the fading radio channel model are studied. In addition, sensitivity of the proposed adaptive algorithm with respect to the algorithm parameters is discussed.

Chapter 5 concludes the thesis.

Chapter 2

Distributed Link Scheduling Algorithms

In this chapter, link scheduling algorithms in wireless networks and their distributed implementations are discussed. Furthermore, simulation results for the link scheduling algorithms proposed in [1] and [2] are presented. After the discussion of these simulation results, possible problems of the scheduling algorithms for radio channels under fading are introduced and the effects of these problems on the real-time applications such as “Skype” are discussed.

2.1 Link Scheduling

In wireless networks, transmission in the same frequency band creates interference problem among transmitting nodes. If all the transmitters and receivers in the wireless network operate in the same frequency band, signals cannot be successfully received if the interference is high. This is because unintended in-band signals cannot be filtered out and noise on the signals cause erroneous results and packets cannot be delivered as intended. If the resulting interference on the received signal is higher than a threshold value for successful reception, the interfering transmission should not be allowed to occur concurrently with the ongoing transmission.

This problem is solved by the *link scheduling algorithm.* Link scheduling is the decision of which of the links in the network should have transmission at a given time instant due to the interference constraint. This problem becomes more complex if the number of interfering links increases. For mathematical solutions to be presented for this problem, interfering links are assumed to be neighbors and links in the network are modeled by an interference graph [1],[2] which will be presented in Section 2.2.

2.2 Network Model and Assumption in Basic Scheduling Algorithms

A wireless network can be modeled by a conflict graph $G = (V, E)$, where V represents the nodes and E represents the links in the wireless network [1],[2]. Nodes in the conflict graph represent wireless transceivers. Links that are neighbors in the conflict graph interfere with each other if they have transmissions concurrently.

In order to represent the interfering links of link $i \in E$ analytically, $C(i)$ is defined so that links in $C(i)$ interfere with link i [1],[2]. It is assumed that, if $i \in C(j)$ then $j \in C(i)$, meaning if link i interferes with another link j, correspondingly link j interferes with link i [1],[2].

A "feasible schedule" of $G = (V, E)$ is a combination of links that can be active in transmission simultaneously, i.e., transmissions on the links in a feasible schedule experience no interference [1],[2]. M is defined as the set of the possible feasible schedules of the network [1],[2].

In the network model, it is assumed that only one packet can be transmitted in a given time slot by each link, according to the feasible schedule [1],[2]. A feasible schedule can be modeled by a vector $x \in \{0,1\}^{|E|}$ where the i^{th} entry of x represents the transmission state of link $i \in E$ at that time [1],[2]. If i^{th} entry of x is "0", link i does not have transmission, otherwise i^{th} entry is "1" [1],[2].

The capacity region of the network is defined as the set of all arrival rates λ where the network can be kept stable [1],[2]. The capacity region [5] is defined as:

$$\Lambda = \{\lambda | \exists \mu \in ConH(M), \lambda < \mu\} \tag{2.1}$$

where $ConH(M)$ is the convex hull of the set of schedules in M.

A scheduling algorithm is "throughput optimum", if the stability for the wireless network can be achieved for arrival rates in capacity region [1],[2].

2.3 Scheduling Algorithm

In this thesis, the scheduling algorithm considered in [1],[2] is used as the basic scheduling algorithm. In this basic scheduling algorithm, each time slot is composed of a "control" and a "data" slot [1],[2]. In the control slot, a feasible schedule is obtained, which will be used in the decision for data transmission in the data slot. For this purpose, first, any non-interfering link combination of the wireless network is chosen which is denoted by $m(t)$. $m(t)$ does not directly correspond to the transmission schedule but transmission schedule is determined according to $m(t)$, which is called the "decision schedule" in time slot t [1],[2].

$M_0 \subseteq M$ is defined as the set of possible feasible decision schedules in the wireless network [1],[2]. A feasible decision schedule is chosen by the network randomly i.e., $m(t) \in M_0$ is chosen with probability $\alpha(m(t))$ such that $\sum_{m(t)\in M_0} \alpha(m(t)) = 1$ where $\alpha(m)$ is the probability mass function (pmf) of the decision schedules [1],[2]. After selecting the decision schedule, the transmission schedule is defined according to the procedure described next.

2.3.1 Basic Scheduling Algorithm ([1],[2])

Basic scheduling algorithm is a simple scheduling algorithm to be implemented. The control phase is used first to create a feasible schedule and in the next phase, links decide whether to be in transmission or not. This control phase makes basic scheduling algorithm to be implemented in a distributed way as will be discussed in Section 2.4. The algorithm is given as:

```
1. In the control slot, a decision schedule $m(t) \in M_0$ is chosen with probability $\alpha(m(t))$:
  $\forall i \in m(t)$:
    If none of the links in $C(i)$ were in transmission in the previous data slot
      (a) $x_i(t) = 1$ with probability $p_i, 0 < p_i < 1$
      (b) $x_i(t) = 0$ with probability $\bar{p_i} = 1 - p_i$
    Else
      (c) $x_i(t) = 0$
  $\forall i \notin m(t)$
      (d)$x_i(t) = x_i(t-1)$
```

2. In the data slot, links, denoted with “1”s in $x(t)$, have transmission.

2.3.2 Throughput Optimality

One of the most important properties that should be considered in the scheduling algorithms is the throughput optimality, where throughput is the average rate of successful packet delivery in the network. In the literature, powerful algorithms have been proposed, which are centralized and achieves throughput optimality. The most important centralized approach that has been of interest in the field of throughput optimality is the “Maximum Weight Scheduling (MWS)” [5], which has given insight for the distributed scheduling algorithms.

In MWS, each link $i \in E$ is associated with a weight $w_i(t)$ in time slot t. MWS algorithm chooses the transmission schedule $x^\star(t)$ in every time slot t [1],[2] such that:

$$\sum_{i \in x^\star(t)} w_i(t) = max_{x \in M} \sum_{i \in x} w_i(t) \tag{2.2}$$

$q_i(t)$ represents the queue-length of link i in time slot t. MWS is proved to be throughput optimum when $w_i(t) = q_i(t)$ [5]. In [24], the condition on the link weights for achieving throughput optimality is defined as follows:

MWS is throughput optimum if link weights are $w_i(t) = f(q_i(t))$, where possible functions $f : [0, \infty] \rightarrow [0, \infty]$ that satisfy:

(1) $f(q_i)$ is a nondecreasing, continuous function with $\lim_{q_i \rightarrow \infty} f(q_i) = \infty$

(2) Given any $C_l > 0$, $C_h > 0$ and $0 < \epsilon < 1$, there exists a $Q_h < \infty$, such that for all $q_i > Q_h$ and $\forall i$,

$$(1-\epsilon)f(q_i) \leq f(q_i - C_l) \leq f(q_i + C_h) \leq (1+\epsilon)f(q_i)$$

Then, the following result is achieved.

Theorem 1 ([24]): Given any ϵ and δ, $0 < \epsilon$, $\delta < 1$, if there is $W > 0$ such that in any time slot t, the scheduling algorithm selects the transmission schedule $x(t) \in M$, with probability larger than $1 - \delta$, that satisfies:

$$\sum_{i \in x(t)} w_i(t) \geq (1-\epsilon) max_{x \in M} \sum_{i \in x} w_i(t)$$

when $\|q(t)\| > W$, then the scheduling algorithm is throughput optimum.

In the basic scheduling algorithm in this thesis, the link activation probability is chosen as $p_i = \frac{e^{w_i(t)}}{e^{w_i(t)}+1}$, $\forall i \in E$. The stationary probabilities of the transmission schedules are given in [1],[2] as:

$$\pi(x) = \frac{1}{Z} \prod_{i \in x} \frac{p_i}{\bar{p}_i} = \frac{1}{Z} \prod_{i \in x} e^{w_i(t)} = \frac{e^{\sum_{i \in x} w_i(t)}}{Z}. \tag{2.3}$$

Based on Theorem 1 and equation (2.3), the following proposition is achieved in [1],[2].

Proposition 2 ([1],[2]) : If the basic scheduling algorithm satisfies $\cup_{m \in M_0} m = E$ and $p_i = \frac{e^{w_i(t)}}{e^{w_i(t)}+1}$, $\forall i \in E$, then the scheduling algorithm is throughput optimum.

2.4 Distributed Implementation of Basic Scheduling Algorithm (Q-CSMA)

Besides the throughput-optimality of the basic scheduling algorithm, unlike MWS, it can be implemented as a distributed scheduling algorithm [1],[2]. The main idea in the distributed implementation is to find a feasible decision schedule $m(t)$ in the control slot part of the basic scheduling algorithm in a distributed way [1],[2]. For this purpose, the control slot of the basic scheduling algorithm is divided into mini-slots. This implementation is called Q-CSMA (Queue-length based CSMA/CA) [1],[2]. The reason is that link activation probabilities of the links are functions of weights, which are increasing functions of the queue-lengths and data transmission is provided without interference via carrier sensing by control message exchange [1],[2]. The algorithm is explained in more detail in Section 2.4.1.

2.4.1 Q-CSMA Algorithm ([1],[2])

In each control slot, every link $i \in E$ is associated with a random back-off time to send its INTENT message to its neighbors in the control mini-slot corresponding to that back-off time. If any link receives an INTENT message, that link is excluded from the decision schedule $m(t)$, so that a feasible decision schedule is obtained, which will be used in the selection of feasible transmission schedule in the basic scheduling algorithm.

The algorithm is summarized as follows:

1. Link i chooses a random back-off time T_i uniformly from set $[0\ W\text{-}1]$ where W is the number of control mini-slots in the control slot. Then link i waits for

T_i control mini-slots.

2. If link i receives an INTENT message from any link in $C(i)$ before the $(T_i + 1)$-th control mini-slot, link i will not be included in $m(t)$ and will not transmit an INTENT message in that control slot. Thus, $x_i(t) = x_i(t-1)$.

3. If link i does not receive an INTENT message from any link in $C(i)$ before $(T_i + 1)$-th control mini-slot, it will transmit an INTENT message to the links in $C(i)$ in the beginning of $(T_i + 1)$-th control slot:

If there is collision, meaning any other link in $C(i)$ transmits an INTENT message in the same control mini-slot, link i is not included in $m(t)$ so that $x_i(t) = x_i(t-1)$.

If there is no collision, link i will be included in $m(t)$ and link i decides its state as transmitting or not as follows:

If none of the links in $C(i)$ were in transmission in the previous slot:

$x_i(t) = 1$, with probability $p_i, 0 < p_i < 1$,

$x_i(t) = 0$, with probability $\bar{p}_i$, where $\bar{p}_i = 1 - p_i$,

Else

$x_i(t) = 0$.

4. If $x_i(t) = 1$, link i transmits the packet in data slot.

By decision schedule selection in a distributed way, basic scheduling algorithm becomes a throughput optimum distributed scheduling algorithm, since other steps in the procedure are made link-wise individually. In Section 2.5, this distributed algorithm is improved for achieving lower delay.

2.5 Low-Delay Hybrid Q-CSMA Algorithm

According to the simulations in [1], it is observed that, the delay performance of the Q-CSMA algorithm is quite poor when the packet arrival rate to the network is high. Furthermore, its performance is much worse than the Greedy Max Weight Scheduling (GMS) in which, sequentially, link with the maximum weight is selected and its neighbors are eliminated. The problem with GMS is that GMS is proved not to be throughput optimum for all network topologies. However, unlike MWS which is proved to be throughput optimum, GMS can be implemented in a distributed way, by using a similar approach used in the Q-CSMA algorithm [1]. This is because GMS is much more relaxed version of the MWS. By using INTENT message exchange between neighbors, if the link with maximum queue-length is given transmission opportunity first, GMS is implemented in a distributed way [1]. Thus, a new algorithm is designed for lower delays in the network.

This new algorithm is a distributed link scheduling algorithm consisting of both Q-CSMA and distributed GMS and a queue threshold which determines which algorithm should be used. Since better results are obtained in GMS when compared to Q-CSMA, GMS is applied for any link $i \in E$ if queue-length of link i is less than the threshold. On the other hand, if the queue-length of link i is above the queue-length threshold, Q-CSMA algorithm is applied. In this case, since the throughput optimality of Q-CSMA is proven in Theorem 1 as $q_i \to \infty$ in [1], the throughput optimality of this new algorithm is also proven as $q_i \to \infty$. This combined algorithm in [1] is called "Hybrid Q-CSMA". The algorithm is described in more detail in Section 2.5.1

2.5.1 Hybrid Q-CSMA Algorithm ([1])

In the Hybrid Q-CSMA algorithm, delay performance of the Q-CSMA algorithm is intended to be improved, without violating the throughput optimality. In Hybrid Q-CSMA, each link $i \in E$ first checks its own queue whether to use distributed GMS or Q-CSMA. If the queue-length of the link i is above the threshold, link i uses Q-CSMA algorithm. The important part of the algorithm is the distributed implementation of the GMS part. Since links with higher queue-lengths have priority on sending the INTENT message, links with higher queue-lengths silence their neighbors. If these links are taken into transmission schedule without any condition, distributed GMS algorithm is implemented directly. Because of the collisions in INTENT message exchange, distributed GMS shows quite poor performance when compared to centralized GMS. However, by choosing the control slot length larger, the probability of collisions may be decreased. The algorithm is given as follows:

IF $q_i(t) > q_0$ (Q-CSMA procedure)

1.1 Link i chooses a random back-off time $T_i = Uniform[0, W_0 - 1]$.

1.2 If link i receives an INTENT message from a link in $C(i)$ before the $(T_i + 1)$-th control mini-slot, then $x_i(t) = x_i(t-1)$ and go to step 1.4.

1.3 If link i does not receive an INTENT message from any link in $C(i)$ before $(T_i + 1)$-th control mini-slot, it transmits an INTENT message to all links in $C(i)$ at the beginning of $(T_i + 1)$-th control mini-slot.

If there is collision, $x_i(t) = x_i(t-1)$.

If there is no collision, link i will determine its state as follows:

If none of the links in $C(i)$ were in transmission due to Q-CSMA procedure in previous data slot, ie, $NA_i = 0$

$x_i(t) = 1$ with probability $p_i, 0 < p_i < 1$.

$x_i(t) = 0$ with probability $\bar{p_i}, \bar{p_i} = 1 - p_i$.

Else

$x_i(t) = 0$.

1.4 If $x_i(t) = 1$, link i will transmit an RESV message to all links in $C(i)$ at the beginning of th $(W_0 + 1)$-th control mini-slot. It will set $NA_i = 0$ and transmit a packet in the data slot.

If $x_i(t) = 0$ and link i receives an RESV message from any link in $C(i)$ in the $(W_0 + 1)$-th control mini-slot, link i will set $NA_i = 1$; otherwise $NA_i = 0$.

IF $q_i(t) \leq q_0$ (D-GMS PROCEDURE)

2.1 If link i receives an RESV message from any link in $C(i)$ in the (W_0+1)-th control mini-slot, link i will set $NA_i = 1$ and $x_i(t) = 0$ and stay silent in this time slot; otherwise, link i will set $NA_i = 0$ and choose a random back-off time $T_i = (W_0 + 1) + W_1 * [B - log_b(q_i(t) + 1)]^+ + Uniform[0, W_1 - 1]$ and wait for T_i control mini-slots.

2.2 If link i receives an RESV message from a link in $C(i)$ before the $(T_i + 1)$-th control mini-slot, $x_i(t) = 0$ and link i will stay silent in this time slot.

2.3 If link i does not receive an RESV message from any link in $C(i)$ before (T_i+1)-th control mini-slot, it will transmit an RESV message to all links in $C(i)$ at the beginning of $(T_i + 1)$-th control mini-slot.

If there is a collision, $x_i(t) = 0$.

If there is no collision, $x_i(t) = 1$.

2.4 If $x_i(t) = 1$, link i will transmit a packet in data slot.

2.6 Simulation Results for Average Queue-Length Performance in Ideal Wireless Environment

The following 24 link topology is used for the performance analysis of all the algorithms in terms of average queue-length. We further assume that no bit errors occur during wireless transmissions. Arrivals occur according to a bernoulli distribution.

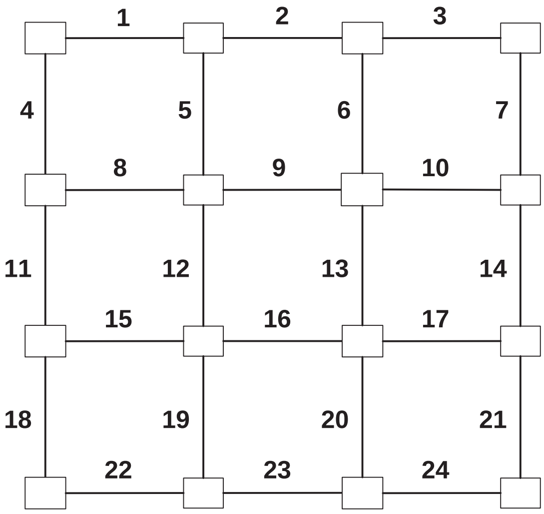


Figure 2.1: 24-link Grid Topology

To be able to make comparison with results in [1],[2], the parameter setting for the algorithms are as follows:

GMS: $B = 3, W = 16; b = 8$

Q-CSMA: W=48; $w_i(t) = log(0.1q_i(t))$ and $p_i = \frac{e^{w_i(t)}}{e^{w_i(t)}+1}$

Hybrid Q-CSMA: $W_0 = 5$, $B = 3$ and $W_1 = 14$ for the GMS procedure plus 1 transition mini-slot. $q_0 = 100$; $w_i(t) = log(0.1q_i(t))$ and $p_i = \frac{e^{w_i(t)}}{e^{w_i(t)}+1}$

As represented in [1],[2], 4 possible schedules consisting of maximum number of links for 24-link grid topology are shown with s_i's and the arrival rate vector is:

$$\{1,3,8,10,15,17,22,24\} \in s_1 \ , \ \{4,5,6,7,18,19,20,21\} \in s_2$$
$$\{1,3,9,11,14,16,22,24\} \in s_3 \ , \ \{2,4,7,12,13,18,21,23\} \in s_4$$

Arrival rate vector: $\lambda = \rho . \sum_{i=1}^{4} k_i s_i, k_1 = 0.2, k_2 = 0.3, k_3 = 0.2, k_4 = 0.3$

where s_i is a vector representing the schedule with jth index as "1" if link j is in s_i and as "0" if link j does not exist in s_i.

After setting the parameters, average queue-lengths are given as a function of ρ in Figure 2.2.

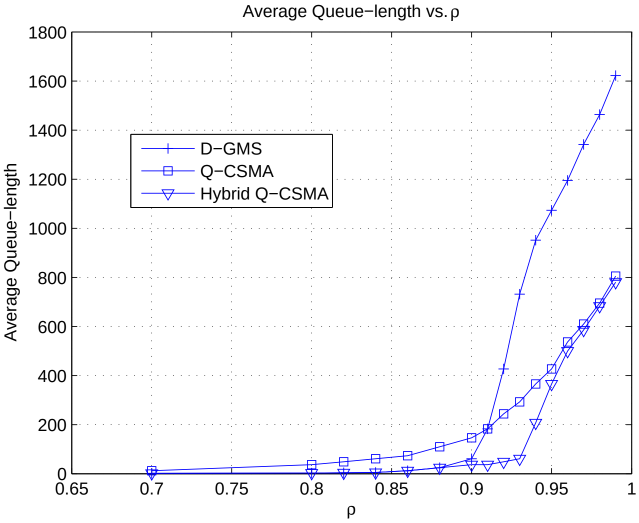


Figure 2.2: Average queue-length vs. ρ for 24-link Grid Topology

The results obtained in these simulations show the same behavior as the ones obtained in [1] and [2]. When arrival rates are low, distributed GMS algorithm works better, when compared to Q-CSMA. However, distributed GMS works worse when arrival rates increase. Hybrid Q-CSMA algorithm uses advantages of both algorithms.

2.7 Transient Behavior of Scheduling Algorithms

In order to determine the weaknesses of the algorithms, the transient behavior of Q-CSMA and distributed GMS are shown in Figures 2.3 and 2.4, respectively when $\rho = 0.9$ for link 1.

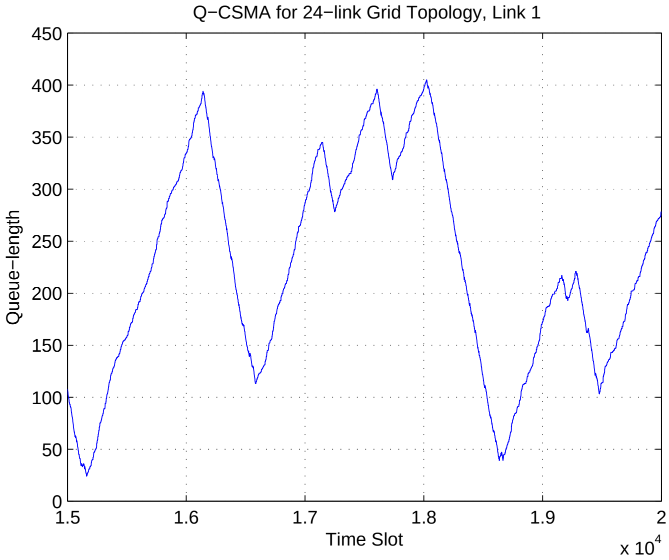


Figure 2.3: Transient analysis of Link 1 in 24-link Grid Topology for Q-CSMA algorithm

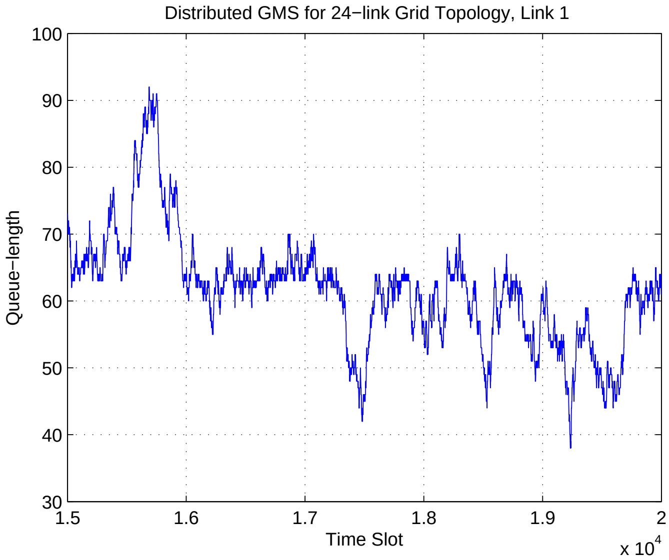


Figure 2.4: Transient analysis of Link 1 in 24-link Grid Topology for distributed GMS algorithm

When the transient behavior of the algorithms is analyzed, the queue-lengths of the links evolve in triangular manner in the Q-CSMA algorithm. The reason is that when any link $i \in E$ is selected in the Q-CSMA algorithm in one time slot, it is harder to deactivate link i in future time slots. This is because if link i is not scheduled in the decision schedule $m(t)$, it goes on transmission for a while. Even though it is selected in the decision schedule, since activation probability is proportional to the queue-lengths and queue-lengths are high, link i will be included in the transmission schedule with very high probability. Thus, for any link i in one transmission schedule to be deactivated, link i should be scheduled by $m(t)$ and queue-length of link i should decrease enough for deactivation. As a result, variance in queue-lengths increases, which directly increases the variance of delay. In addition, since a link chosen has an important effect on its neighbors' queue-lengths, once any link $i \in E$ is selected in the transmission schedule, queue-lengths of the links in $C(i)$ grow, which directly increases the maximum delay in the network.

When practical systems are considered, "Bit Error Rates (BER)" cannot be simply ignored. In case of fading, many erroneous packet transmissions occur due to the increase in BER; thus, adaptive modulation and coding (AMC) scheme is introduced to decrease BER in wireless applications [3]. However, there is a trade-off between BER and data rate in the systems using AMC, which should be considered by the link scheduling algorithms. When distributed GMS is considered in a fading propagation environment, there seems to be not much problem since link activation depends on the present situation. However, when Q-CSMA algorithm is considered, once a link is selected during a fade, it is difficult to deactivate that link. As a result, because of low data rate, in that link, huge queue-lengths and respectively huge delays will be observed. Besides, since the deactivation gets harder, the neighbors' performance will also be affected negatively.

In this thesis, we focus on this subject and propose a performance improvement technique by making a channel state estimation on each link and sharing this information with the neighbors. Since states of the links are defined using a small set, a small overhead in the control slot will be generated. This improvement has important effects on the average and maximum delay in the network, which may be critical for real-time applications such as "Skype". In Chapter 4, different approaches that use this information will be presented.

Chapter 3

Time-varying Fading Radio Channel Model

In this chapter, an analytical model for time-varying channels is presented. First, adaptive modulation and coding (AMC) scheme, which is widely used in wireless communication protocols is introduced. In addition, its application areas and supported AMC profiles have been analyzed for better characterization of the wireless medium. Furthermore, fading concept is introduced and the effects of “small scale fading” in radio channels are analyzed.

3.1 Adaptive Modulation and Coding (AMC)

In wireless communication networks, the need for high data rates increases rapidly. In order to increase data rates in transmissions, modulation types with higher constellations should be used. However, symbols used for data transmission in wireless medium are exposed to transmission errors due to distance between transmitters and receivers, fading, shadowing, interference, noise etc. If a symbol is not successfully received by the receiver, the bits carried by that symbol are received erroneously. As a drawback, when an error occurs in the data transmission, using modulation types with higher constellations results in more erroneous bits to be received, which degrades the spectral efficiency in the network. To provide good quality of service, according to the current condition of the channel, optimum modulation type should be selected.

Some error correction mechanisms have been introduced to fix the errors in the transmissions. As an error correction mechanism, Forward Error Correction (FEC) is widely used in wireless communication protocols. In FEC, besides the data bits, additional bits are sent by the transmitters. Small errors observed in the transmissions are fixed in the receiver side by using these additional parity bits. However, using additional bits degrades the data rate in the wireless network, so that the number of additional bits to be used is an important aspect, which is defined by the coding rate. Coding rate represents how much of the bits carried in one symbol are data bits. In order to increase the spectral efficiency in the network, according to the condition of the radio channel, optimum modulation type and the coding rate should be correctly set.

Adaptive modulation and coding (AMC) aims to provide good quality of service in order to improve the efficiency in data transmissions in the networks with time-varying channel. In AMC, best possible modulation type and coding rate pair is selected for transmission among the possible profiles such that the targeted BER is satisfied under the assumed channel model. With AMC, even though the channel condition is time-varying, BER for transmission is kept nearly constant during the transmission and good quality of service is provided. AMC is used in several protocols such as IEEE 802.11a, IEEE 802.15.3 and IEEE 802.16

etc. [25],[26],[27],[28],[29],[30].

Possible AMC profiles used by WiMAX are given in Table 3.1, which will be used in the determination of the time-varying fading radio channel model that will be developed in Section 3.6.

Table 3.1: Burst profiles supported by WiMAX [3]

Modulation	Overall coding rate
BPSK	1/2
QPSK	1/2
QPSK	3/4
16-QAM	1/2
16-QAM	3/4
64-QAM	1/2
64-QAM	2/3
64-QAM	3/4
64-QAM	5/6

3.2 Fading and Small-Scale Fading

In wireless medium, received signal is exposed to significant variation in its amplitude and phase. “Fading”” is defined as the variation in attenuation that the signal transmitted is exposed to, over the radio channel. In wireless systems, fading may occur because of the shadowing of the obstacles between the transmitter and the receiver. This is called “shadow fading”, which is time-dependent because the positioning of the obstacles may vary with time. In addition, fading may occur, because of the reflections of the transmitted signal from the walls, trees, vehicles etc. These reflections, called “multi-paths”, are also received by the receiver, which affects the signal power at the receiver side. This type of fading is called “multi-path fading” [3], which is also time-dependent. Signals that experience fading may observe amplification or attenuation in its power so that fading directly affects the quality of transmission in wireless medium.

In this thesis, the effect of mobility is considered in a way that, the neighborhood does not change significantly, which is a similar case to fixed deployment of transmitters and receivers. As a result, fading problem becomes “small-scale fading” problem, which refers to changes in signal amplitude and phase according to small variations [3]. This may be a result of small variations in the positions of the transmitters and the receivers deployed in the network [3] or the small changes in the environment.

Statistical work has been carried out in literature for the distribution of small-scale fading, however, it is not possible to define a general fading distribution, since it depends on the geography. In this work, we model the fading process by using fading rate and average fade duration statistics.

3.3 Stanford University Interim (SUI) Channel Models

Stanford University Interim (SUI) channel models bring important contributions to the work by AT&T Wireless and Erceg et al [31]. The effect of distance between transmitters and receivers, shadowing, fading, doppler shift etc. are all realistically modeled, so that SUI channel models give great insight about radio channel propagation. SUI channel models consist of 6 channels to define 3 different regions experimented on the continential US [23]. The properties of these 6 channels are tabulated in Table 3.2.

Table 3.2: Terrain type for SUI channels [3]

Terrain Type	SUI Channels
C (Flat terrain with small number of trees)	SUI-1,SUI-2
B (Hilly terrain with small number of trees or flat terrain with large number of trees)	SUI-3,SUI-4
A (Hilly terrain with large number of trees)	SUI-5,SUI-6

3.3.1 Bit Error Rate (BER) Analysis for SUI Channel Models

There is a strong trade-off between robustness to errors and the data rate in transmission due to the channel conditions. When the Signal-to-Noise Ratio (SNR) at the receiver gets lower, the signal becomes comparable with the noise level, where it is more possible to experience errors in the data transmission. However, using AMC profiles with smaller constellations and with lower coding rates decreases the BER while decreasing the data rate and spectral efficiency. In order to increase the spectral efficiency in the network, BER vs. SNR results for each AMC profile should be carefully examined and best possible AMC profile should be preferred for transmission according to the condition of radio channel. In Figures 3.1, 3.2 and 3.3, BER vs. SNR results for all AMC profiles supported by 802.16 are given for SUI-1, SUI-2 and SUI-3 channel models, respectively.

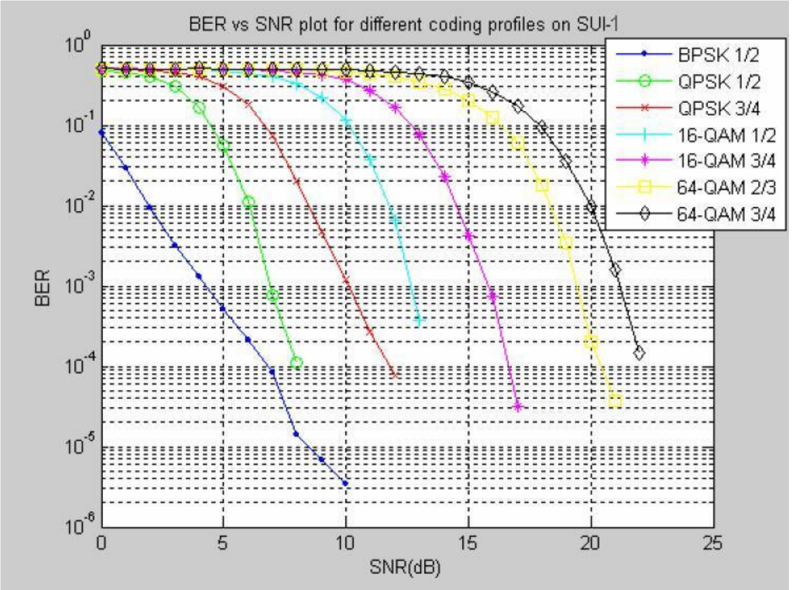


Figure 3.1: BER vs. SNR plot for different AMC profiles for SUI-1 channel [3]

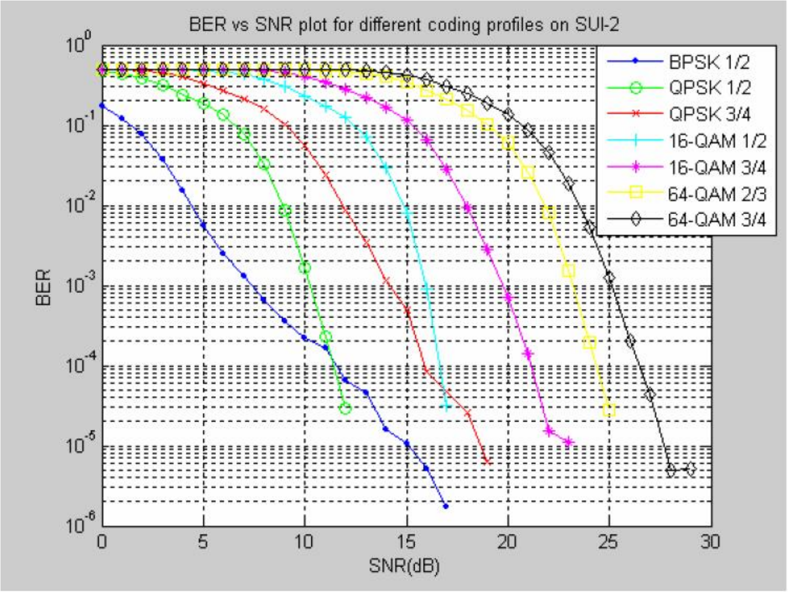


Figure 3.2: BER vs. SNR plot for different AMC profiles for SUI-2 channel [3]

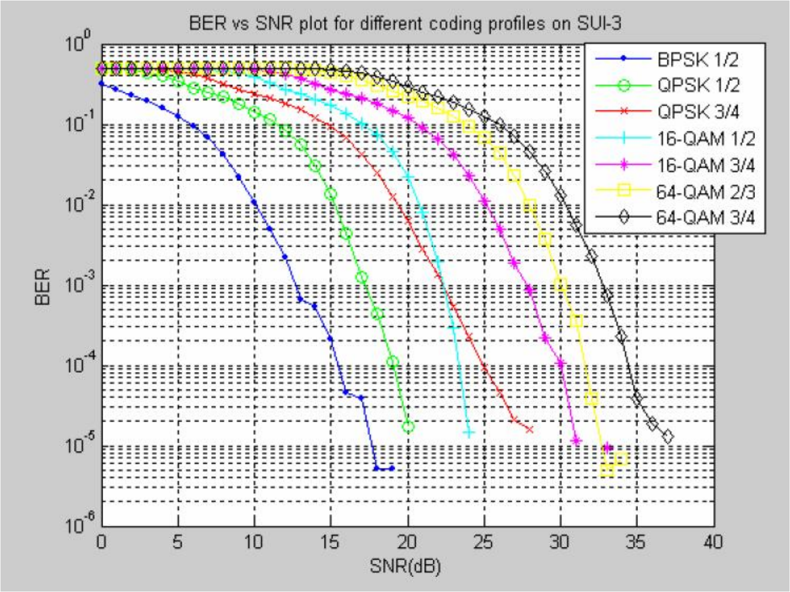


Figure 3.3: BER vs. SNR plot for different AMC profiles for SUI-3 channel [3]

In order to provide the highest data rate to the network, according to the threshold SNR values for the targeted BER, best possible AMC profile may be used [3]. For targeting BER level at 10^{-3}, threshold SNR values for possible AMC profiles are tabulated in Table 3.3.

Table 3.3: SNR required at BER level 10^{-3} for different profiles in SUI channel models [3]

Modulation	BPSK	QPSK	16-QAM	64-QAM
Coding rate Channel	1/2	1/2	1/2	2/3
SUI-1	4.3	6.6	12.3	19.4
SUI-2	7.5	14.1	16.25	23.3
SUI-3	12.7	17.2	22.7	30

AMC decides which modulation type and coding rate should be used for the spectral efficiency of the network according to the channel conditions of the links in the network. When BER are observed as a function of SNR, if SNR values are lower, modulation types with smaller constellations and smaller coding rates should be selected for less erroneous transmissions in the network with the drawback of increase in the queue-lengths and delays of the links. In delay sensitive applications such as “Skype”, packets delivered after their scheduled playout time are useless, so that delays in the transmission play an important role in the efficiency of the network. In delay sensitive applications, AMC should be done not only due to the BER values at certain SNR values but also according to transmission rates for lower delays in the network.

In the time-varying channel model used in this thesis, there are 4 AMC profiles. It would be possible to use all AMC profiles supported by 802.16; however, 4 states give great insight about the conditions of the radio channel. In this thesis, 64-QAM with coding rate 2/3, 16-QAM with coding rate 1/2, QPSK with coding rate 1/2 and BPSK with coding rate 1/2 are selected as possible AMC profiles. In addition, since work on fading distributions have not revealed exact general solutions yet, fading durations are assumed to be exponentially distributed. As a result, links are assumed to change their burst profiles according to a 4-State Continuous Time Markov Chain (CTMC) where the parameters of the 4-State CTMC will be determined in Section 3.6.

3.4 Spectral Efficiency

Spectral Efficiency is a significant concept in wireless communication. In this thesis, as in [3], spectral efficiency is defined as:

$$SE = (1 - p_e)^{n_b} n_s c_r \tag{3.1}$$

where, p_e: the bit error rate, n_b: the number of bits in the block, n_s: the number of bits per symbol, c_r: the coding rate.

In Figure 3.4, the spectral efficiencies of the 4 burst profiles used in this thesis are plotted for the SUI-3 channel model.

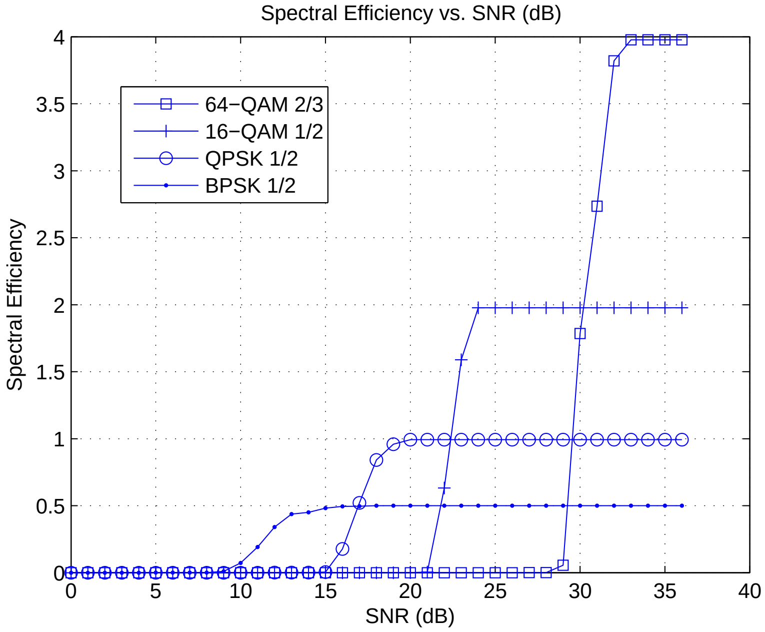


Figure 3.4: Spectral efficiencies of the 4 burst profiles for SUI-3 channel model due to BER vs. SNR results in [3] for SUI-3 channel

Only 4 AMC profiles are used in this thesis, which are 64-QAM 2/3, 16-QAM 1/2, QPSK 1/2 and BPSK 1/2. According to Figure 3.4, approximate threshold SNR values where these profiles are no longer spectral efficient, are tabulated in Table 3.4.

Table 3.4: Minimum SNR values required for different burst profiles for spectral efficiency in SUI 3

Burst Profile	Minimum SNR value required for the burst profile	Spectral Efficiency (b/s/Hz)
64-QAM 2/3	30 dB	4
16-QAM 1/2	23 dB	2
QPSK 1/2	18 dB	1
BPSK 1/2	10 dB	0.5

The relation between SNR degradation and the selected burst profile is given in Table 3.5.

Table 3.5: Burst profiles used under different ranges of fade depths in SUI 3

Burst Profile	SNR Degradation (dB)
64-QAM 2/3	SNR Degradation $<$ 3 dB
16-QAM 1/2	3dB $<$ SNR Degradation $<$ 10dB
QPSK 1/2	10dB $<$ SNR Degradation $<$ 15dB
BPSK 1/2	SNR Degradation $>$ 15 dB

These SNR thresholds play an important role in the determination of the transition rates of 4-state CTMC which determine the background how the links in the network change their burst profiles for transmission and correspondingly the dynamics of the network in wireless environment. In Section 3.5, Level Crossing Rates (LCR) and Average Duration of Fades (ADF) for SUI channels will be presented, so that LCR and ADF values at these SNR thresholds will determine the transition rates of the CTMC model for time-varying channels.

3.5 Level Crossing Rate and Average Duration of Fades in SUI Channels

In wireless environment, transmitted signal experiences deviation in its power. For characterization of fading in radio channels, statistical information about the rate of fading in time-varying channel and fade durations are necessary, which are given by “Level Crossing Rate (LCR)” and “Average Duration of Fades (ADF)”, respectively.

3.5.1 Level Crossing Rate(LCR)

Level Crossing Rate (LCR) is one of the important concepts in examining fading. LCR represents the rate of the degradation in signal amplitude under a certain level [4]. In the time-varying channel model, 4 different SNR regions should be specified in order to determine the states of the CTMC model for radio channel conditions. Assuming the signal SNR is 33 dB when there is no fading, first state change will be done in -3 dB fade as shown in Figure 3.4. In addition, the other important LCR values are at -10 dB and -15 dB. In Figure 3.5, LCR in SUI-3 channel is shown for different bandwidths.

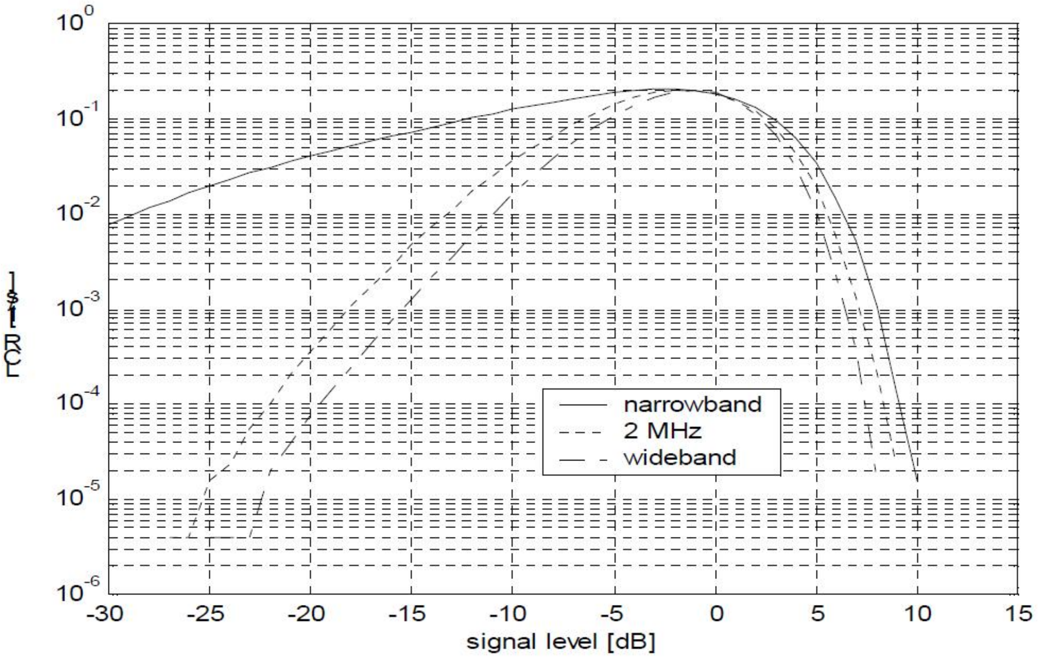


Figure 3.5: LCR for different Fade Depths in SUI-3 channel [4]

The LCR values at the interested fade depths when bandwidth is 2 MHz are tabulated in Table 3.6.

Table 3.6: LCR values at interested fade depths

Interested dB Level	LCR
-3 dB	0.2
-10dB	0.03
-15dB	0.005

3.5.2 Average Duration of Fades (ADF)

Besides LCR, Average Duration of Fades (ADF) is also important in defining fading in SUI channels. ADF function defines the average time spent under that SNR level [4], which gives an important idea on the duration of fades and the CTMC that will be developed. The ADF vs. Fade Depth in dB is shown in Figure 3.6.

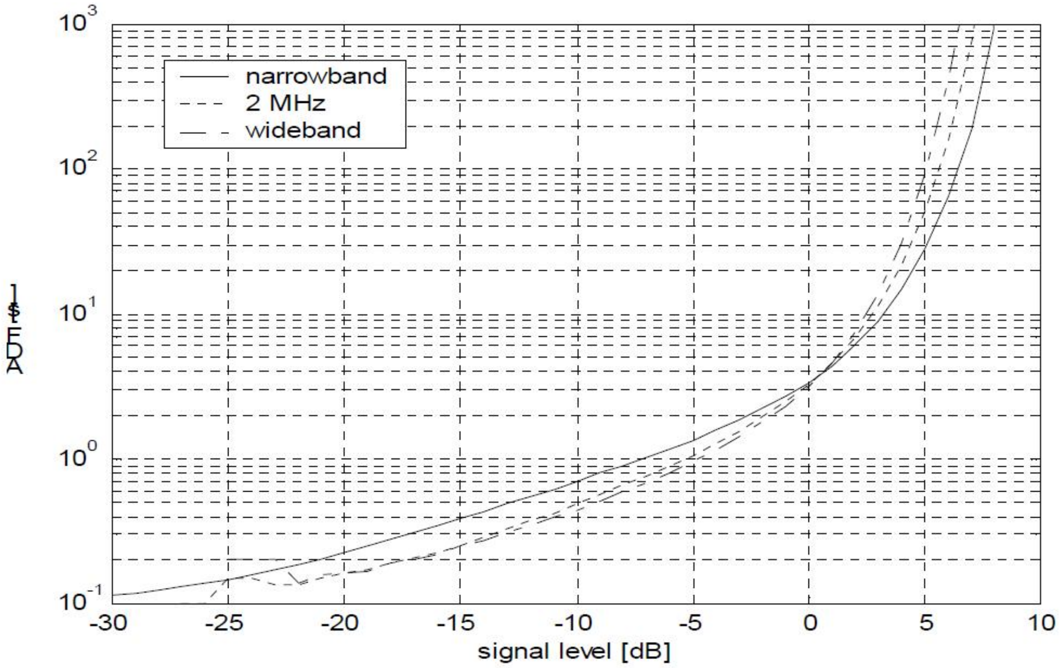


Figure 3.6: ADF for different Fade Depths in SUI-3 channel [4]

ADF values at -3 dB, -10 dB and -15 dB are important, which are tabulated in Table 3.7.

Table 3.7: ADF values at interested fade depths

Interested dB Level	Approximate ADF (in secs)
-3 dB	1.5
-10dB	0.5
-15dB	0.25

In Section 3.6, by using the LCR and ADF values, a 4-state CTMC will be constructed for the time-varying channel model.

3.6 Time-varying Fading Channel Model

In this thesis, we assume that the fading durations are exponentially distributed. As a result, fading and correspondingly data rates of the links are modeled by a 4-State CTMC as shown in Figure 3.7:

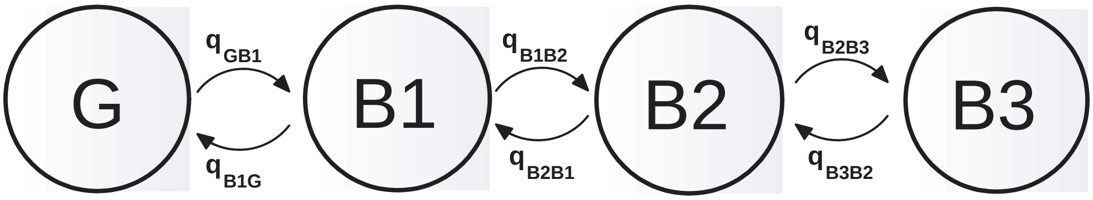


Figure 3.7: 4-state CTMC, modeling time-varying fading radio channel

where,

G : Good State(SNR degradation < 3 dB)

B1: 3 dB < SNR degradation < 10 dB

B2: 10 dB < SNR degradation < 15 dB

B3: 15 dB < SNR degradation

The stationary probabilities of the CTMC can be found in an iterative way by using LCR and ADF values. Since LCR values represent crossings below certain level, first, the stationary probability of the state B3 should be found by using LCR (-15 dB) and ADF (-15 dB). Afterwards, by using LCR (-10 dB) and ADF (-10 dB), the sum of the stationary probabilities of states B2 and B3 can be obtained, where stationary probability of B2 and all the other 2 stationary probabilities can be found in an iterative way:

$$\pi_{B3} = LCR(-15dB).ADF(-15dB) = 0.00125 \tag{3.2}$$

$$\pi_{B2} + \pi_{B3} = LCR(-10dB).ADF(-10dB) = 0.015 \iff \pi_{B2} = 0.01375 \tag{3.3}$$

$$\pi_{B1} + \pi_{B2} + \pi_{B3} = LCR(-3dB).ADF(-3dB) = 0.3 \iff \pi_{B1} = 0.285 \tag{3.4}$$

$$\pi_G = 1 - (\pi_{B1} + \pi_{B2} + \pi_{B3}) \iff \pi_G = 0.7 \tag{3.5}$$

After obtaining the stationary probabilities of the CTMC, the forward rates of the CTMC can be obtained as follows:

$$\pi_G.q_{GB_1} = LCR(-3dB) \iff q_{GB_1} = 0.2857 \tag{3.6}$$

$$\pi_{B_1}.q_{B_1B_2} = LCR(-10dB) \iff q_{B_1B_2} = 0.1053 \tag{3.7}$$

$$\pi_{B_2}.q_{B_2B_3} = LCR(-15dB) \iff q_{B_2B_3} = 0.3636 \tag{3.8}$$

After obtaining the forward rates of CTMC, backward rates can be obtained from the detailed balance equations (DBE) as follows:

$$\pi_{B_2}.q_{B_2B_3} = \pi_{B_3}.q_{B_3B_2} \iff q_{B_3B_2} = 4 \tag{3.9}$$

$$\pi_{B_1}.q_{B_1B_2} = \pi_{B_2}.q_{B_2B_1} \iff q_{B_2B_1} = 2.1826 \tag{3.10}$$

$$\pi_{G}.q_{GB_1} = \pi_{B_1}.q_{B_1G} \iff q_{B_1G} = 0.7017 \tag{3.11}$$

The resulting transition rates of the CTMC are tabulated in Table 3.8.

Table 3.8: Transition rates of the 4-State CTMC, modeling time-varying fading radio channel

Rates of 4-State CTMC	Values
q_{GB_1}	0.2857
$q_{B_1B_2}$	0.1053
$q_{B_2B_3}$	0.3636
$q_{B_3B_2}$	4
$q_{B_2B_1}$	2.1826
q_{B_1G}	0.7017

To be used in the simulations, state transition probabilities and the mean time spent in each state are given as follows:

$$Mean(G) = \frac{1}{q_{GB_1}} = 3.5002 \tag{3.12}$$

$$p_{GB_1} = 1 \tag{3.13}$$

$$Mean(B_1) = \frac{1}{q_{B_1B_2} + q_{B_1G}} = 1.2392 \tag{3.14}$$

$$p_{B_1B_2} = \frac{q_{B_1B_2}}{q_{B_1B_2} + q_{B_1G}} = 0.1305 \tag{3.15}$$

$$p_{B_1G} = 1 - p_{B_1B_2} = 0.8695 \tag{3.16}$$

$$Mean(B_2) = \frac{1}{q_{B_2B_1} + q_{B_2B_3}} = 0.3927 \tag{3.17}$$

$$p_{B_2B_3} = \frac{q_{B_2B_3}}{q_{B_2B_3} + q_{B_2B_1}} = 0.1428 \tag{3.18}$$

$$p_{B_2B_1} = 1 - p_{B_2B_3} = 0.8572 \tag{3.19}$$

$$Mean(B_3) = \frac{1}{q_{B_3B_2}} = 0.25 \tag{3.20}$$

$$p_{B_3B_2} = 1 \tag{3.21}$$

After finalizing the time-varying fading radio channel model, in order to analyze the validity, LCR and ADF values at the transition regions are obtained according to the simulations. The resulting LCR and ADF values according to the 4-State CTMC model are tabulated in Tables 3.9, 3.10, respectively.

Table 3.9: LCR values at interested fade depths according to the simulations

Interested dB Level	ADF (in secs)
-3 dB	0.205
-10dB	0.029
-15dB	0.005

Table 3.10: ADF values at interested fade depths according to the simulations

Interested dB Level	LCR
-3 dB	1.499
-10dB	0.501
-15dB	0.247

The resulting LCR and ADF values according to the 4-State CTMC model for time-varying radio channel are so close to exact LCR and ADF values for SUI-3 channel, which shows the validity of the model.

In order to give insight about how the channel condition of a link changes through time, in Figure 3.8, according to the 4-State CTMC model for time-varying fading radio channels, SNR degradation as a function of time for a sample link is demonstrated.

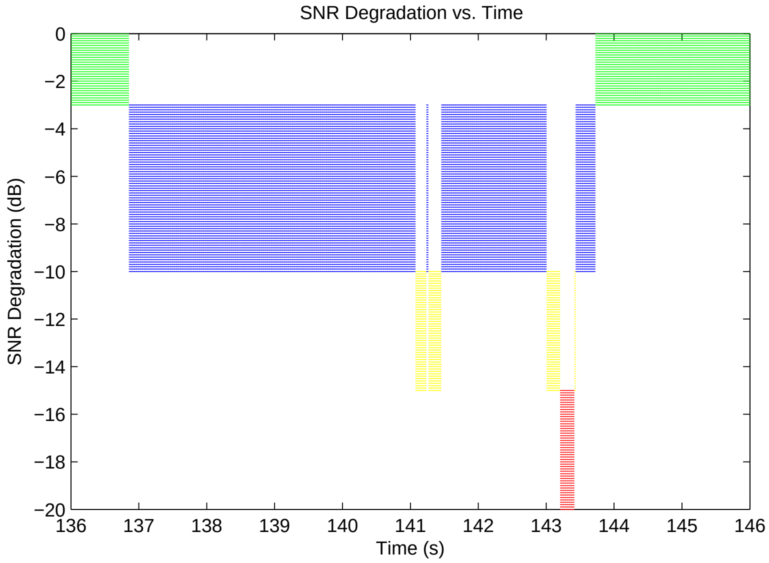


Figure 3.8: SNR Degradation of the channel for a sample link through time

In Chapter 4, the delay performance of the Hybrid Q-CSMA is analyzed under the 4-state CTMC time-varying fading radio channel model developed in this chapter. In addition, for delay sensitive applications, channel aware link scheduling approaches such as "Full Opportunistic Algorithm" and "Delay Based Adaptive Algorithm" are proposed in order to increase the probability of successful packet receptions in wireless networks with time-varying channels.

Chapter 4

Channel Aware Link Scheduling

In this chapter, the performances of the scheduling algorithms under the fading radio channel model proposed in Chapter 3 are studied. In addition, two new link scheduling algorithms, “Full Opportunistic Algorithm” and “Adaptive Scheduling Algorithm” have been proposed to improve the delay performance of the Hybrid Q-CSMA algorithm. The performances of the algorithms are tested by simulations using different topologies. In addition, a new metric “Effective Goodput” is defined to analyze the delay performance for delay sensitive applications. In the end of this chapter, the sensitivity of the adaptive algorithm on the algorithm parameters is analyzed and the extensions of the approaches for delay aware transmitter based networks are introduced.

4.1 Problems in Hybrid-QCSMA Algorithm

According to the Hybrid Q-CSMA algorithm, when the queue-lengths are higher than the threshold q_0, Q-CSMA algorithm is used. In the Q-CSMA algorithm, queue-lengths of the links evolve in a triangular manner. The reason for this is that, once any link $i \in E$ is chosen in the transmission schedule, link i goes on transmission for a long a time. This is because the deactivation of link i requires that it is chosen by the decision schedule $m(t)$ and the queue-length of link i is relatively small. This situation gives links in $C(i)$ no transmission opportunity during this ongoing transmission, which increases their queue-lengths. This is not a problem in ideal wireless environment, where no fading is present since the scheduling algorithm is able to keep the network stable with its throughput optimum nature. However, in time-varying radio channels, when fading occurs, the burst profile changes, creating larger delays and packet losses in the network due to missed playout times.

In addition, even in the GMS part of the Hybrid Q-CSMA algorithm, for link i under fading, transmission rate decreases so that giving transmission opportunity to links in $C(i)$ which are not under fading may increase the delay efficiency of the network. In GMS part of the Hybrid Q-CSMA algorithm, schedule is chosen according to the present queue-lengths of the links only, so that the modifications in this part may have small improvements on the spectral efficiency of the network, when compared to Q-CSMA part.

4.2 Channel State Aware Scheduling Algorithms

Scheduling algorithms introduced in Chapter 2 assume that the radio channel is ideal, meaning there is no fading. In ideal wireless environment, there is no need for the links to be aware of the channel conditions. However, in time-varying radio channels, data rates in the transmissions of the links depend on the AMC scheme, where the awareness about the channel condition for each link becomes significant. Since links under fading have lower data rates when compared to links with better channel conditions, channel state awareness improves the delay performance of the network.

Each link in the network may determine its channel condition by simple SNR estimation. In addition, because of the nature of the Hybrid Q-CSMA, before the transmission schedule is chosen, a message exchange between the links may be done in the wireless network. If each link sends its channel condition within the shared message packet, each link in the network receives the channel condition of its neighbors in the network. Since each link's channel may be in one of the four states under the fading radio channel model described in Chapter 3, additional two-bit information on the messages does not significantly increase the overload. In this thesis, because of the nature of Hybrid Q-CSMA, each link is assumed to know the channel state of its neighbors in the network and its own. Based on this assumption, in order to increase the delay efficiency of Hybrid Q-CSMA algorithm under time-varying radio channels, two different improvements are proposed.

4.2.1 Full Opportunistic Algorithm

In the "Full Opportunistic Algorithm", the fading conditions of the links and the neighboring links are assumed to be known by each link. In this approach, to prevent packet losses due to timeout, it is considered that if any link $i \in E$ is in "Good" state (meaning there is no fading), the Hybrid Q-CSMA scheduling policy will be applied. However, if link i goes under fading, and if at least one link in $C(i)$ is in better channel condition, giving no transmission opportunity to link i, will help links in $C(i)$ with better channel conditions to access the channel. As a result, high probability of success is achieved when total throughput is considered, since overall transmission rate is higher in the network. In addition to this, if all the links in $C(i)$ are in the same channel condition, even though they are under fading, Hybrid Q-CSMA scheduling policy should be applied. This is because, instead of not using any links for medium access, using some of the links would increase the throughput. This also does not violate the "fairness" in the network.

Giving no transmission opportunity to any link $i \in E$ under fading creates problems when the load of the network is considerably small. Assume any link $i \in E$ is under fading. Since less arrivals occur to the network and the network is stable, queue-lengths of the links in $C(i)$, which are in "Good" state, are mostly "0". Instead of activating link i under fading, giving transmission opportunity to links in $C(i)$ which have empty queues, is inefficient since no transmission will be done in those links. In addition, by not activating link i, transmission in link i is refused. Since mean time spent under fading is large for a link, the refuse of these transmissions increases the queue-length of link i, without providing spectral efficiency for the wireless network.

In order to overcome this problem, besides the channel quality information, "Empty Queue" information should also be shared. "Empty Queue" information can be embedded with the channel condition information shared in the beginning of each transmission schedule decision and each link knows the 'Empty Queue" information of its own and its neighbors. This information sharing creates a more efficient transmission schedule selection.

With these improvements, the Hybrid Q-CSMA algorithm is modified with parameter α_{max}, which is a huge constant that will make p_i approximately "0", indicating no transmission opportunity is given. In the "Full Opportunistic Algorithm", Hybrid Q-CSMA algorithm is modified in 1.3 and 2.3.

1.3 If link i does not receive an INTENT message from any link in $C(i)$ before $(T_i + 1)$-th control mini-slot, it will transmit an INTENT message to all links in $C(i)$ at the beginning of $(T_i + 1)$-th control mini-slot

If there is collision, $x_i(t) = x_i(t-1)$.

If there is no collision, link i will determine its state as follows:

If none of the links in $C(i)$ were in transmission due to Q-CSMA procedure in previous data slot, ie, $NA_i = 0$

If link i is under fading & at least one link in $C(i)$ is in a better state & all links in $C(i)$ have non-empty queues

$p_i = \frac{e^{w_i(t)}}{e^{w_i(t)}+\alpha_{max}}$.

Else

$p_i = \frac{e^{w_i(t)}}{e^{w_i(t)}+1}$.

$x_i(t) = 1$ with probability $p_i, 0 < p_i < 1$.

$x_i(t) = 0$ with probability $\bar{p_i}, \bar{p_i} = 1 - p_i$.

Else

$x_i(t) = 0$.

And,

2.3 If link i does not receive an RESV message from any link in $C(i)$ before $(T_i + 1)$-th control mini-slot

If link i is under fading & at least one link in $C(i)$ is in a better state

& all links in $C(i)$ have non-empty queues, link i will stay silent and $x_i(t) = 0$.

Else it will transmit an RESV message to all links in $C(i)$ at the beginning of $(T_i + 1)$-th control mini-slot.

If there is a collision, $x_i(t) = 0$.

Else, $x_i(t) = 1$.

The following result holds for the "Full Opportunistic Algorithm".

Theorem 2: "Full Opportunistic Algorithm" achieves throughput optimality.

Proof :

Link activation probabilities in this case $p_i(x) = \frac{e^{w_i(t)}}{e^{w_i(t)}+\alpha_i(t)}$
where $\alpha_i(t) = \alpha_{max}$ or $\alpha_i(t) = 1$ according to the condition of link i.
Then Equation (2.3) becomes:

$$\pi(x) = \frac{1}{Z}\prod_{i\in x}\frac{e^{w_i(t)}}{\alpha_i(t)} = \frac{1}{Z}\frac{e^{\sum_{i\in x} w_i(t)}}{\prod_{i\in x}\alpha_i(t)} \tag{4.1}$$

Theorem 1 in Chapter 2 is used to prove the optimality and define the set χ as:

$$\chi := \{x \in M : \textstyle\sum_{i\in x} w_i(t) < (1-\epsilon)w^\star(t)\}$$

Since DTMC has product form distribution:

$$\pi(\chi) = \sum_{x\in\chi}\pi(x) = \sum_{x\in\chi}\frac{1}{Z}\frac{e^{\sum_{i\in x} w_i(t)}}{\prod_{i\epsilon x}\alpha_i(t)} \leq \frac{1}{Z}\sum_{x\in\chi} e^{\sum_{i\in x} w_i(t)} \leq \frac{|\chi|e^{(1-\epsilon)w^\star(t)}}{Z} \tag{4.2}$$

Since $\alpha_i(t) \geq 1$ and $w^\star(t) := max_{x\in M}\sum_{i\in x} w_i(t)$

Thus, a lower bound should be found for Z to complete the proof:

$$Z = \sum_{x\in M}\prod_{i\in x}\frac{e^{w_i(t)}}{\alpha_i(t)} \geq \sum_{x\in M}\prod_{i\in x}\frac{e^{w_i(t)}}{\alpha_{max}} \geq \sum_{x\in M}\frac{e^{\sum_{i\in x} w_i(t)}}{\alpha_{max}^{|E|}} \geq \frac{e^{max_{x\in M}\sum_{i\in x} w_i(t)}}{\alpha_{max}^{|E|}} = \frac{e^{w^\star(t)}}{\alpha_{max}^{|E|}} \tag{4.3}$$

where $\alpha_{max} = max(\alpha(t))$.

Thus using (4.2) and (4.3)

$$\pi(\chi) \leq \frac{|\chi|(\alpha_{max}^{|E|})}{e^{\epsilon w^\star(t)}} \leq \frac{2^{|E|}(\alpha_{max}^{|E|})}{e^{\epsilon w^\star(t)}} \tag{4.4}$$

where $|\chi| \leq |M| \leq 2^{|E|}$

If,

$$w^\star(t) > \frac{1}{\epsilon}(|E|(log(2) + log(\alpha_{max})) + log(\frac{1}{\delta})) \tag{4.5}$$

then

$$\pi(\chi) < \delta$$

$w^\star(t)$ is a continuous and nondecreasing function of $q_i(t)$'s and $\lim_{\|q(t)\| \to \infty} w^\star(t) = \infty$ so that there is a $W > 0$ such that when $\|q(t)\|$ is larger than W, equation (4.5) is satisfied and $\pi(\chi) < \delta$.

"Full Opportunistic Algorithm" is simple to implement. However, the algorithm does not make use of information about the queue-lengths of the links. This situation may create larger increases in the queue-lengths of the links under fading, which decreases the delay efficiency of the network because of the packet losses due to timeout in delay sensitive applications. In Section 4.2.2, we propose "Adaptive Scheduling Algorithm" to further improve the delay efficiency in the network by making use of the delays of the packets in the wireless links.

4.2.2 Delay Based Adaptive Scheduling Algorithm

When “Full Opportunistic Algorithm” is used, since no transmission opportunity is given to any link $i \in E$ under fading, there exists an increase in the maximum delay of link i, even though most of the packets in the overall network are delivered in shorter delays. Since the delay of link i increases rapidly in “Full Opportunistic Algorithm”, packet losses due to timeout may occur. In order to overcome this problem, “Adaptive Scheduling Algorithm” is proposed, which checks whether the delay of link i is likely to exceed the scheduled playout time or not. If the delay of link i under fading is likely to exceed the scheduled playout time, then link i is allowed to get opportunity for transmission by the Hybrid Q-CSMA scheduling policy to decrease its queue-length and respectively the delay of the packets in the buffer. If the delay of link i is not likely to create any packet losses due to timeout, “Full Opportunistic Algorithm” is used to increase the spectral efficiency of the wireless network.

In order to decide whether the packets waiting in the buffers of the links under fading will experience timeout or not, queue-drifts of the links can be estimated. However, relationship between queue-length information and playout time for packets to be delivered successfully is topology dependent. This is because, in more complex topologies, queue-lengths decrease slower since they get less transmission opportunity, when compared to simpler topologies. Since respective playout time for successful delivery is determined by the application, for each topology, corresponding maximum allowable queue-length information should be determined individually, which is inefficient.

On the other hand, the delay information of the links may be used directly to estimate whether there will be a packet loss in the link or not. We assume links operate using the First Come First Serve (FCFS) discipline and compute the delays of the packets waiting in the buffer.

In order to estimate whether there will be a packet loss due to timeout or not, simple threshold check may be used. Assume respective playout time for successful delivery is defined by the application. If the delay of the Head-of-Line packet in the link buffer is higher than some threshold, called d_{low}, then the link may potentially experience packet losses due to timeout. In this situation, Hybrid Q-CSMA procedure is applied for the link to get opportunity in the schedule in order to decrease its queue-length to prevent the packet losses. Otherwise, “Full Opportunistic Scheduling” policy is applied to increase the overall spectral efficiency in the network.

However, in this scheduling algorithm, problems arise, when the delay of any link $i \in E$ under fading exceeds the playout time for successful packet transmission. When link i under fading starts to lose packets because of timeout violation, the adaptive scheduling algorithm gives more transmission opportunity to link i. At higher arrival rates, when packets in the buffer of link i experience timeout, link i is not able to prevent the future packet losses since the transmission rate is not enough for link i to decrease its queue-length. In addition, the queue-lengths of the links in $C(i)$ also increase because they do not have opportunity to access the network, which will create more packet losses in $C(i)$ in future time slots.

In order to deal with this problem, the adaptive algorithm is modified in a way that if the link under fading experiences timeout or the delay of the link is very close to the respective playout time, “Full Opportunistic Algorithm” should be used. By this interpretation, the packets of the link under fading are not saved;

however, the future packets losses that may occur in its neighbors when they go under fading are prevented. The high threshold for the adaptive algorithm to switch back to "Full Opportunistic Algorithm" is denoted by d_{high}.

This approach is called "Delay Based Adaptive Algorithm" and it uses the benefits of both the Hybrid Q-CSMA algorithm and the "Full Opportunistic Algorithm".

The "Delay Based Adaptive Algorithm" can be summarized as follows:

(1) Determine the delay of link i by checking the delay of Head-of-Line packet, i.e. determine $d_{link_i}(t)$ at time t.

(2)If $d_{link_i}(t) < d_{high}$, according to the delay of the link, apply either the Hybrid Q-CSMA Algorithm or the "Full Opportunistic Algorithm"

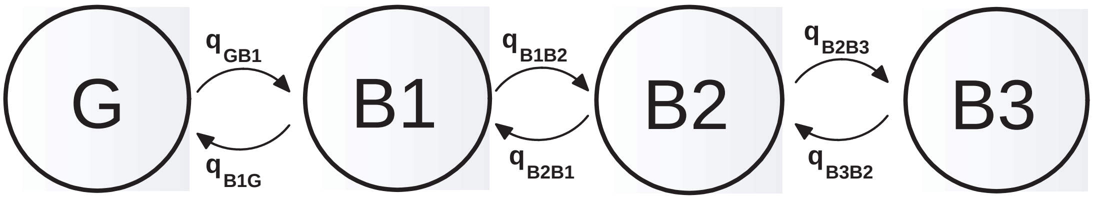
If $d_{link_i}(t) > d_{low}$, then apply the Hybrid Q-CSMA Algorithm.

If $d_{link_i}(t) < d_{low}$, then apply the "Full Opportunistic Algorithm".

(3) If $d_{link_i}(t) > d_{high}$, then apply the "Full Opportunistic Algorithm".

4.3 Simulation Results

The performances of the algorithms under time-varying fading radio channel model are analyzed on different topologies for different packet arrival rates with 4-State CTMC time-varying channel model as shown in Figure 4.1.



where,

G : Good State(SNR degradation < 3 dB
B1: 3 dB < SNR degradation < 10 dB
B2: 10 dB < SNR degradation < 15 dB
B3: 15 dB < SNR degradation)

Figure 4.1: 4-State CTMC, modeling time-varying fading radio channel

In this model, 4 different AMC profiles are used in each state, representing different ranges of fade depths. In the Hybrid Q-CSMA Algorithm, it is assumed that only one packet can be transmitted in each time slot [1]. All packets are also assumed to be identical. To be relevant with the context, assuming full packet transmission is possible in state G, in states B1, B2 and B3, $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$ of the packet will be transmitted respectively according to the spectral efficiencies of the AMC profiles used in these states.

In these simulations, simulation time is set to 50,000 slots and 10 simulations have been carried out for each topology. In addition, in delay sensitive applications, playout time for packets to be delivered successfully is approximately 300ms. Arrivals occur according to a bernoulli distribution.

Parameter setting for the algorithms are as follows:

Hybrid Q-CSMA: $W_0 = 5$, $B = 3$ and $W_1 = 14$ for the GMS procedure plus 1 transition mini-slot. $q_0 = 50$ and $b = 8$. $w_i(t) = log(0.1q_i(t))$ and $p_i = \frac{e^{w_i(t)}}{e^{w_i(t)}+1}$

Full Opportunistic Algorithm: $\alpha_{max} = 100000$.

The delay thresholds of the "Delay Based Adaptive Algorithm" are selected as follows:

$$d_{low}\text{=60 slots}$$
$$d_{high}\text{=150 slots}$$

In addition, a new term, "Effective Goodput" is presented, where

$$EG = p_S.\rho \tag{4.6}$$

where p_S : Probability of reception before timeout

ρ : Arrival rate

In the following subsections, average queue-length, probability of reception before timeout and normalized effective goodput are given as a function of packet arrival rates for the delay performance analysis of the algorithms proposed.

4.3.1 24 link Grid Topology

24-link grid topology is shown in Figure 4.2.

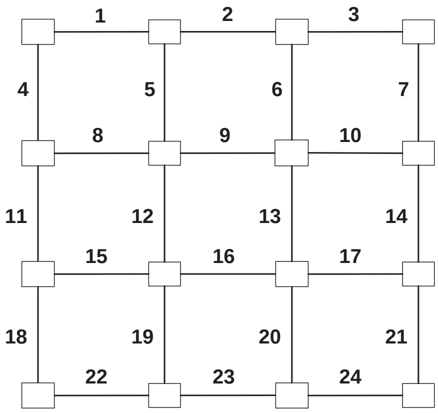


Figure 4.2: 24-link Grid Topology

For 24-links grid topology, to be consistent with the results in [1],[2], performance analysis are given as functions of an arrival rate parameter ρ, which is the scaling of the arrival rate vector.

As represented in [1],[2], 4 possible schedules consisting of maximum number of links for 24-link grid topology are shown with s_i's and the arrival rate vector is:

$$\{1,3,8,10,15,17,22,24\} \in s_1 \ , \ \{4,5,6,7,18,19,20,21\} \in s_2$$
$$\{1,3,9,11,14,16,22,24\} \in s_3 \ , \ \{2,4,7,12,13,18,21,23\} \in s_4$$

Arrival rate vector: $\lambda = \rho . \sum_{i=1}^{4} k_i s_i, k_1 = 0.2, k_2 = 0.3, k_3 = 0.2, k_4 = 0.3$

where s_i is a vector representing the schedule with jth index as "1" if link j is in s_i and as "0" if link j does not exist in s_i.

In Figures 4.3, 4.4 and 4.5, simulation results for average queue-length, probability of successful packet transmission and normalized effective goodput are presented as a function of the packet arrival rate, respectively.

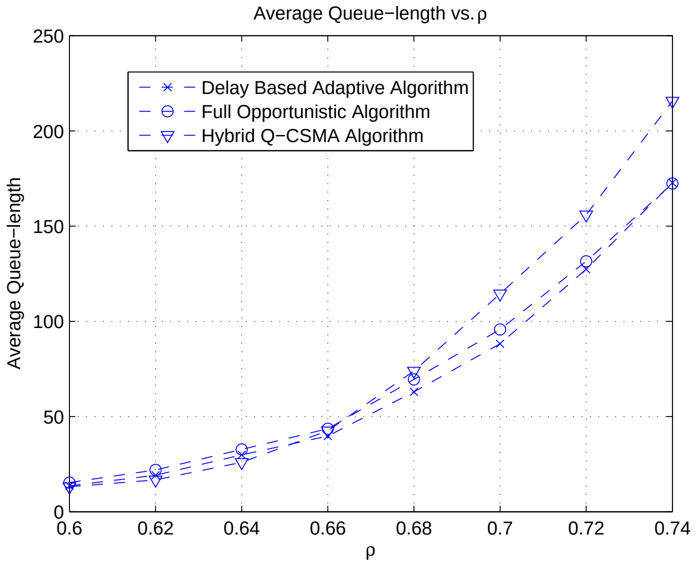


Figure 4.3: Average queue-length vs. arrival rate parameter ρ in 24-link Grid Topology under 4-State CTMC Channel Model

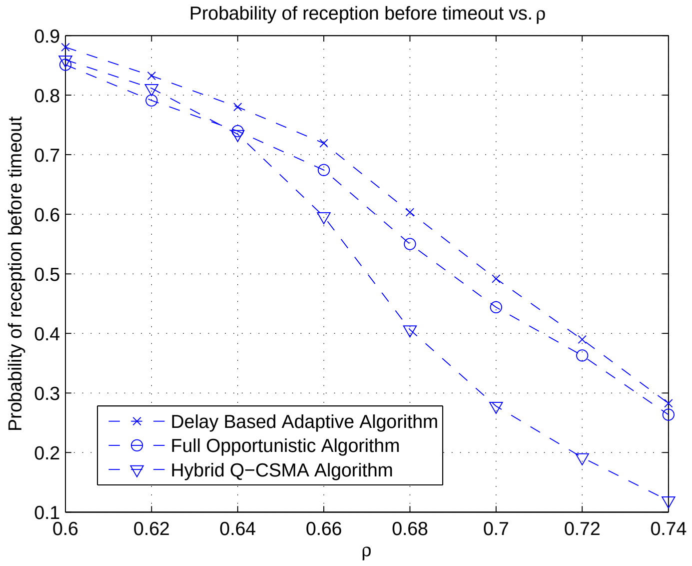


Figure 4.4: Probability of reception before timeout vs. arrival rate parameter ρ in 24-link Grid Topology under 4-State CTMC Channel Model

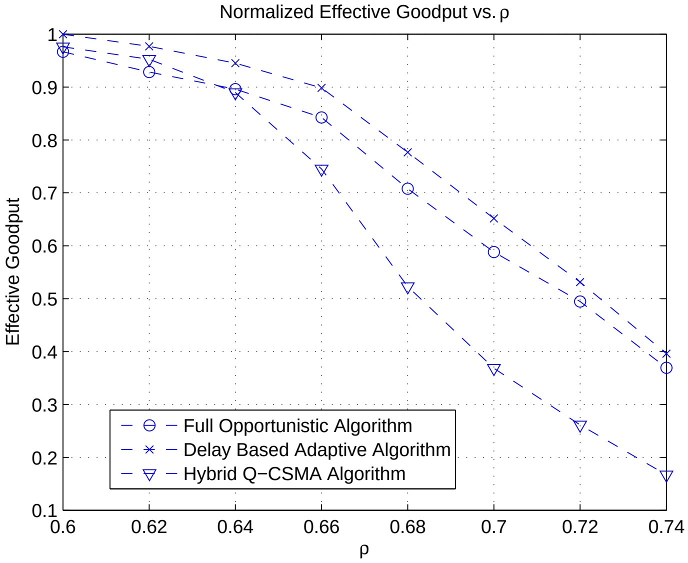


Figure 4.5: Normalized “Effective Goodput” vs. arrival rate parameter ρ in 24-link Grid Topology under 4-State CTMC Channel Model

When the performances of the approaches are considered, at low arrival rates, the “Full Opportunistic Algorithm” does not improve the performance of the Hybrid Q-CSMA scheduling since packets in the queues do not increase significantly. Mostly, the sharing of “Empty Queue” information, clearly solves the problems in low arrival rates. However, when the overload of the network increases, average delays in the network increase and packet losses due to timeout increase in the network. “Full opportunistic Algorithm” performs much better in these regions. Since “Delay Based Adaptive Algorithm” both uses the benefits of “Full Opportunistic Algorithm” and Hybrid Q-CSMA scheduling, it outperforms both algorithms in all arrival regions.

When ρ is higher than 0.7, if Figures 4.4 and 4.5 are carefully examined, the “Delay Based Adaptive Algorithm” nearly doubles the effective goodput achieved by the Hybrid Q-CSMA algorithm in 24-link grid topology. At high arrival rates, a performance improvement of about 20% is achieved by the "Delay Based Adaptive Algorithm" in terms of average queue-lengths.

4.3.2 4-link Line Network

The results in 24-link grid topology show that the improvements on the algorithms clearly provide benefits when delay is considered. For further examinations, the neighborhood relationships should also be considered in the performance improvement. Thus, a more simpler network model consisting of 4-links in a "line" configuration is presented. The network topology is demonstrated in Figure 4.6.

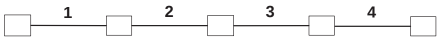


Figure 4.6: 4-link Line Topology

Since network topology is simpler, the performance improvements of the algorithms are expected to be less when compared to the 24-link grid topology. The reason is that not giving transmission opportunity to one link by the "Full Opportunistic Algorithm" will affect less number of links. In addition to this, improvement is expected when arrival rates are low, with the help of "Empty Queue" information.

In this network model, all links are assumed to have the same packet arrival rate, unlike the case in 24-links scenario. In Figures 4.7, 4.8 and 4.9, simulation results for average queue-length, probability of successful packet transmission and normalized effective goodput are presented as a function of packet arrival rate, respectively.

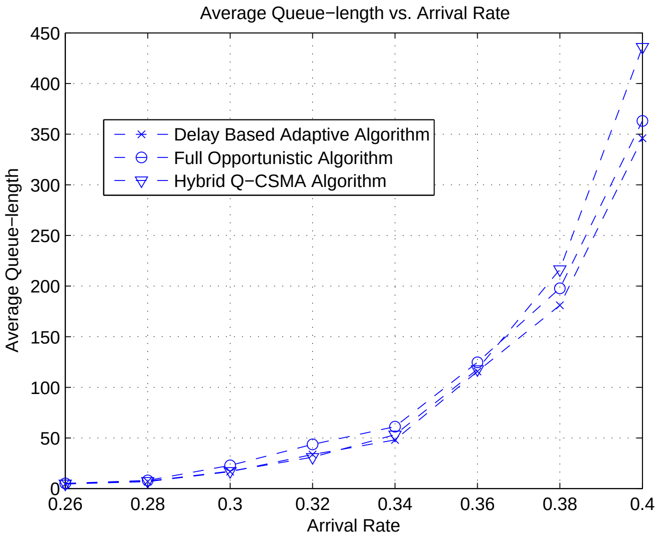


Figure 4.7: Average queue-length vs. arrival rate in 4-link Line Topology under 4-State CTMC Channel Model

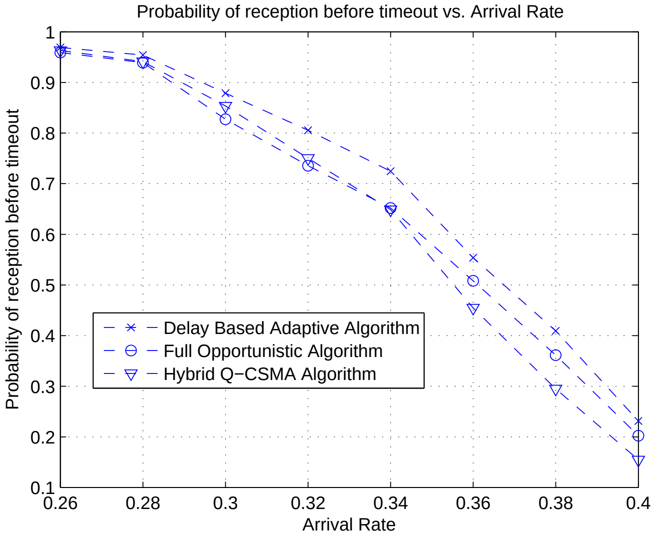


Figure 4.8: Probability of reception before timeout vs. arrival rate in 4-link Line Topology under 4-State CTMC Channel Model

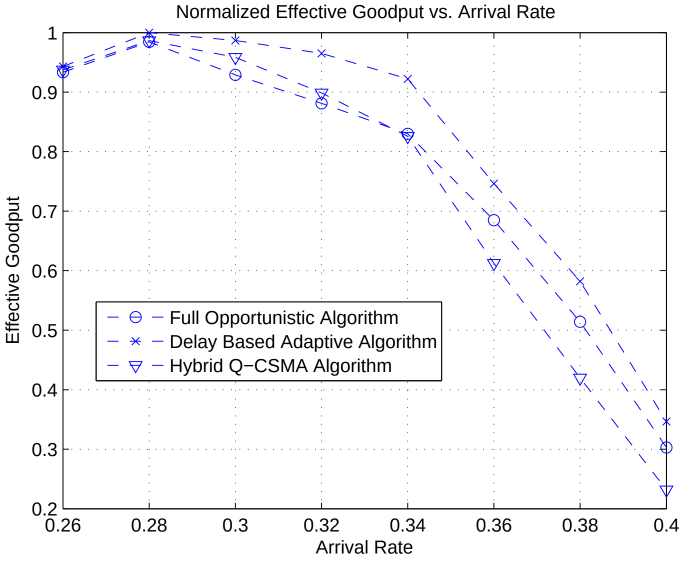


Figure 4.9: Normalized "Effective Goodput" vs. arrival rate in 4-link Line Topology under 4-State CTMC Channel Model

In low arrival rates, performance improvement is less, when compared to higher arrival rates, which is provided mostly, by the "Empty Queue" information shared in the network. "Delay Based Adaptive Algorithm" clearly outperforms in all arrival regions decreasing both packet losses and average queue-length. In addition, the performance improvement is less when compared to the 24-links grid topology because of the neighborhood relationships being simpler. However, with "Delay Based Adaptive Algorithm", nearly 50% performance improvement is observed, when probability of reception before timeout and effective goodput are considered. When average queue-length performances are analyzed, nearly 15% performance improvement is provided by the "Delay Based Adaptive Algorithm".

4.3.3 9-link Circle Network

After observing the neighborhood relationships, the effect of number of links with similar neighborhood relationships should be considered. For this purpose, similar to the 4-link “line” topology, 9-link “circle” topology is examined, which is depicted in Figure 4.10:

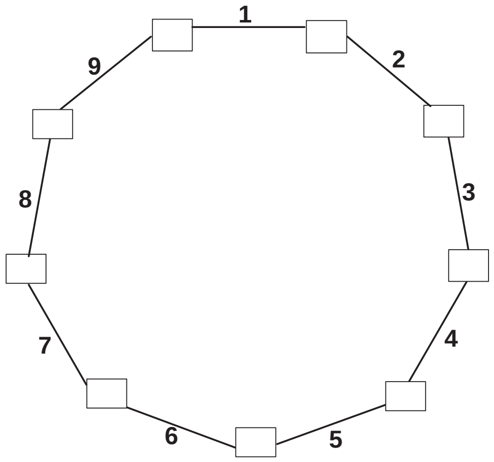


Figure 4.10: 9-link Circle Topology

In this network, all the links have 2 neighbors which is also the simpler version of the 24-link network topology. Unlike the two topologies considered earlier, all nodes have the same number of neighbors in the 9-link topology.

As in 4-link network topology, all arrival rates in this network are assumed to be the same. In Figures 4.11, 4.12 and 4.13, simulation results for average queue-length, probability of successful packet transmission and normalized effective goodput are presented as a function of packet arrival rate, respectively.

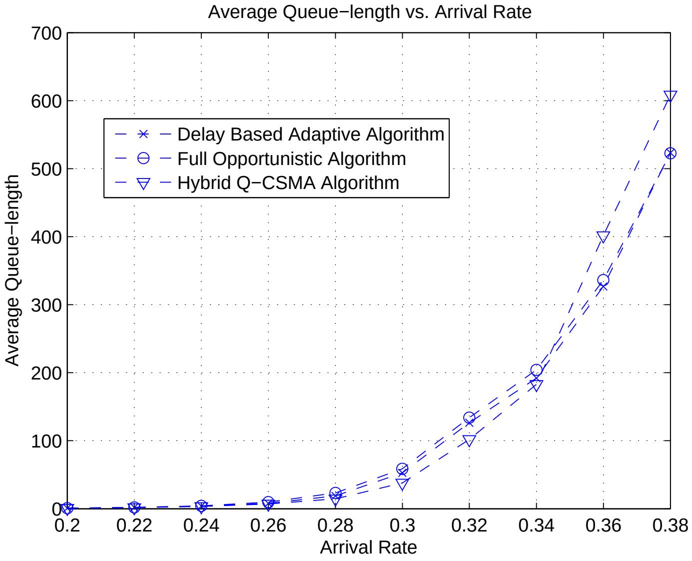


Figure 4.11: Average queue-length vs. arrival rate in 9-link Circle (1-hop Neighborhood) Topology under 4-State CTMC Channel Model

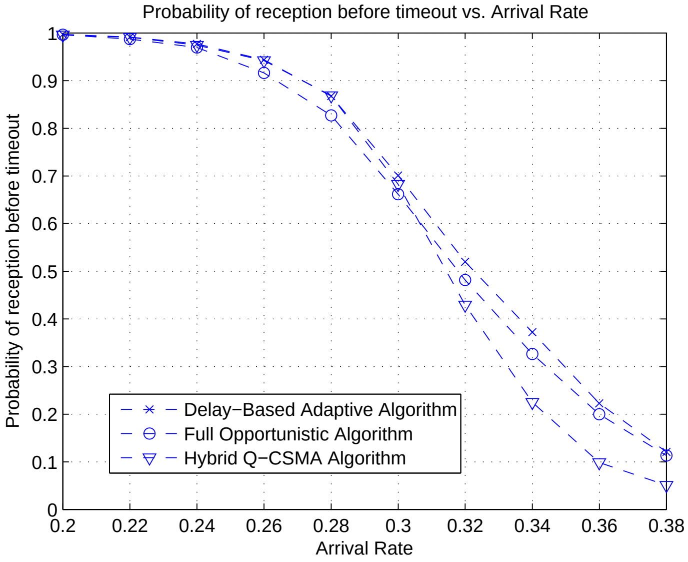


Figure 4.12: Probability of reception before timeout vs. arrival rate in 9-Link Circle (1-hop Neighborhood) Topology under 4-State CTMC Channel Model

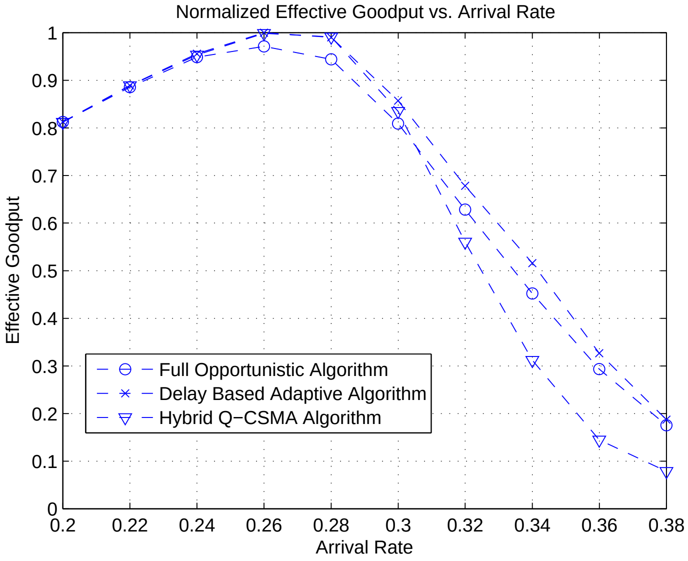


Figure 4.13: Normalized "Effective Goodput" vs. arrival rate in 9-link Circle (1-hop Neighborhood) Topology under 4-State CTMC Channel Model

According to the simulation results, at low arrival rates, performance improvement is small. However, at higher arrival rates, "Full Opportunistic Algorithm" and "Delay Based Adaptive Algorithm" clearly decrease the packet losses due to timeout. At higher arrival rates, average delay is improved by 10%. "Delay Based Adaptive Algorithm" outperforms other algorithms at all arrival rates. At higher arrival rates, about 100% increase in effective goodput is observed in the performance of the "Delay Based Adaptive Algorithm".

4.3.4 9-link Circle Network with Different Neighborhood Relationships

In this network topology, 9-links circle network is used; however, the neighborhood relationships of the network is different. In this topology, each link interferes with the links in the 2-hop neighborhood, meaning each link affects the transmission of 4 links, 2 of which are on the right and 2 of which are on the left.

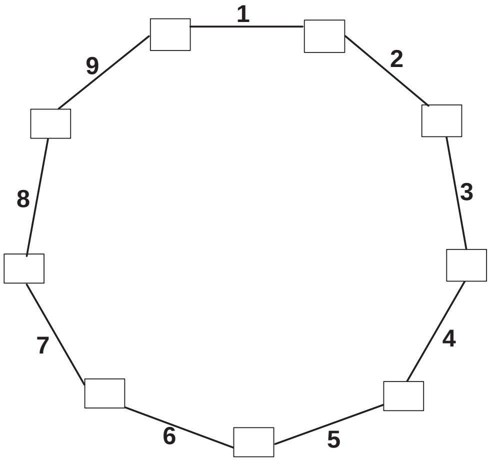


Figure 4.14: 9-links Circle (2-hop Neighborhood) Topology

As an example, assume link 1 is active, then, link 2, link 3, link 9 and link 8 interfere with link 1 during the ongoing transmission so that they should be inactive during transmission.

In this network, arrival rates of links are the same. In Figures 4.15, 4.16 and 4.17, simulation results for average queue-length, probability of successful packet transmission and normalized effective goodput are presented as a function of packet arrival rate, respectively.

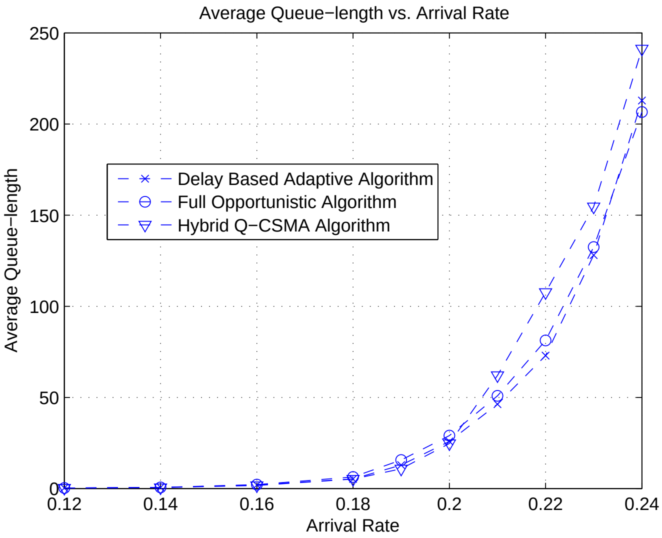


Figure 4.15: Average queue-length vs. arrival rate in 9-link Circle (2-hop Neighborhood) Topology under 4-State CTMC Channel Model

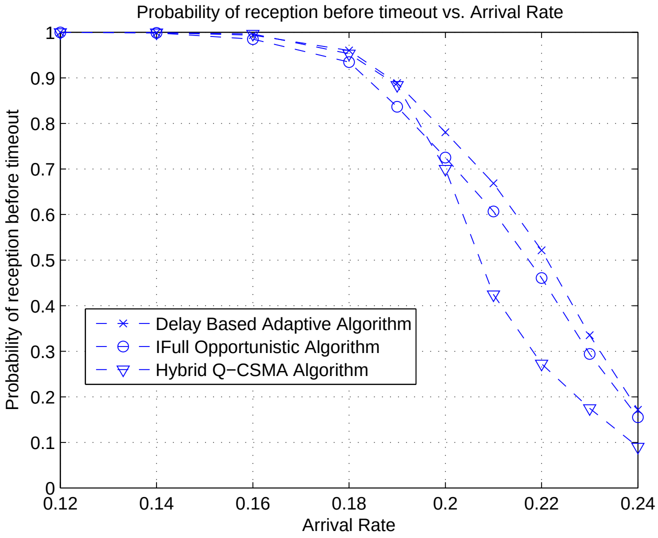


Figure 4.16: Probability of reception before timeout vs. arrival rate in 9-link Circle (2-hop Neighborhood) Topology under 4-State CTMC Channel Model

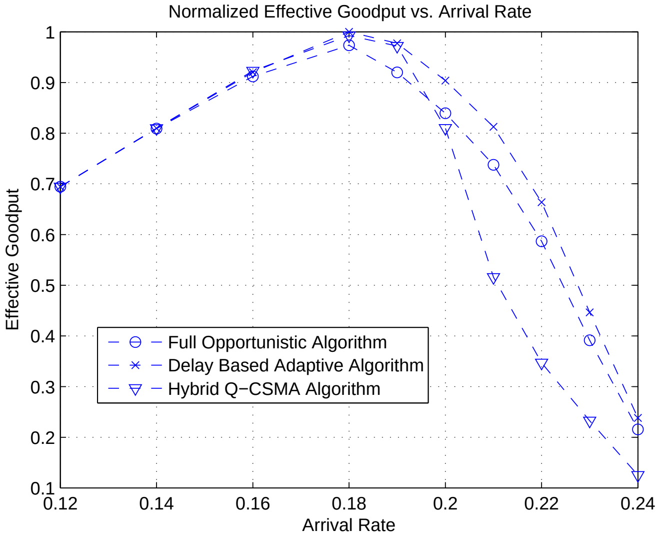


Figure 4.17: Normalized "Effective Goodput" vs. arrival rate in 9-link Circle (2-hop Neighborhood) Topology under 4-State CTMC Channel Model

"Delay Based Adaptive Algorithm" outperforms the other algorithms for all arrival rates. A sharper performance degradation for all algorithms is observed at high traffic load because of increased interference with this topology. When probability of successful reception before timeout and effective goodput are considered, up to 75% performance improvement is provided by "Delay Based Adaptive Algorithm", whereas the average delay is decreased by up to 10%.

4.4 Sensitivity Analysis and Extension of Adaptive Algorithm

In this section, the sensitivity of the "Delay Based Adaptive Algorithm" on the parameters d_{low} and d_{high} is studied. In addition, since delay is known in the transmitters further improvements on the algorithms are presented.

4.4.1 Optimum d_{low} and d_{high} values

In the performance analysis of the algorithms under time-varying fading radio channels, d_{low} and d_{high} values have been selected reasonably, but not in an optimum way. The parameters of the "Delay Based Adaptive Algorithm" have also been selected not in an optimum way. Since optimality depends on the topology and the arrival rates, it is not expected to find the optimum values that are effective for all topologies. The main goal of this section is to observe the effect of d_{low} and d_{high} on the approaches and dependence of the algorithm to these parameters.

For the 24-link grid topology, when $\rho = 0.6$ and $d_{high} = 150$, probability of reception before timeout as a function of d_{low} is plotted in Figure 4.18.

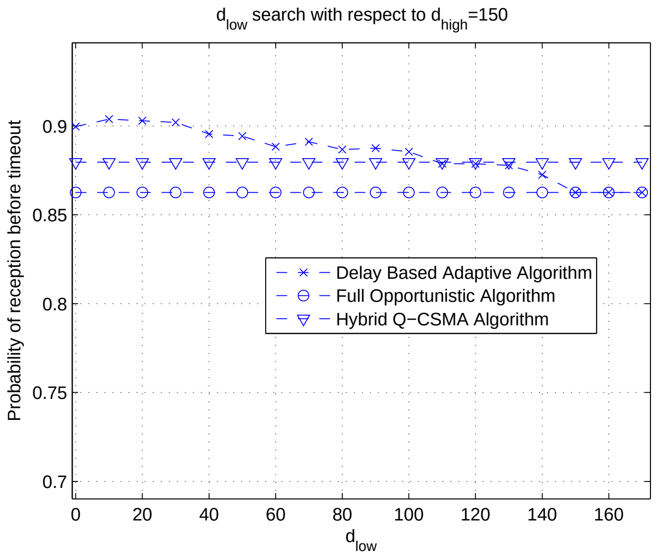


Figure 4.18: Probability of packets delivered before timeout vs. d_{low} in 24-link Grid Topology under 4-State CTMC Fading Radio Channel Model when $\rho = 0.6$

For the 24-link grid topology, when $\rho = 0.6$ and $d_{low} = 60$, probability of reception before timeout versus d_{high} is depicted in Figure 4.19.

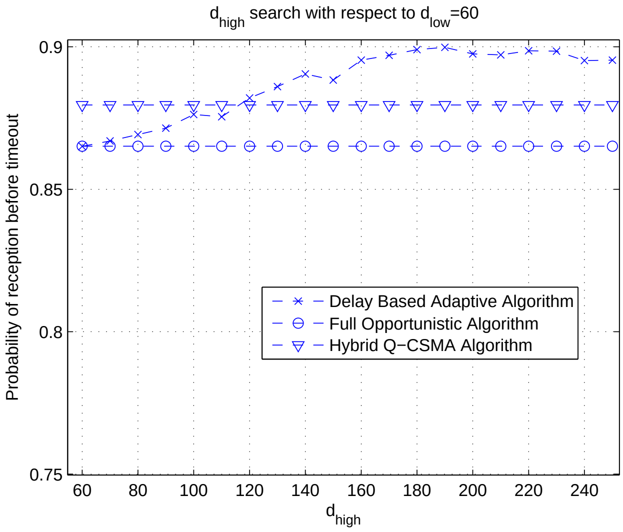


Figure 4.19: Probability of packets delivered before timeout vs. d_{high} in 24-link Grid Topology under 4-State CTMC Fading Radio Channel Model when $\rho = 0.6$

For the 24-link grid topology, when $\rho = 0.72$ and $d_{high} = 150$, probability of reception before timeout as a function of d_{low} is plotted in Figure 4.20.

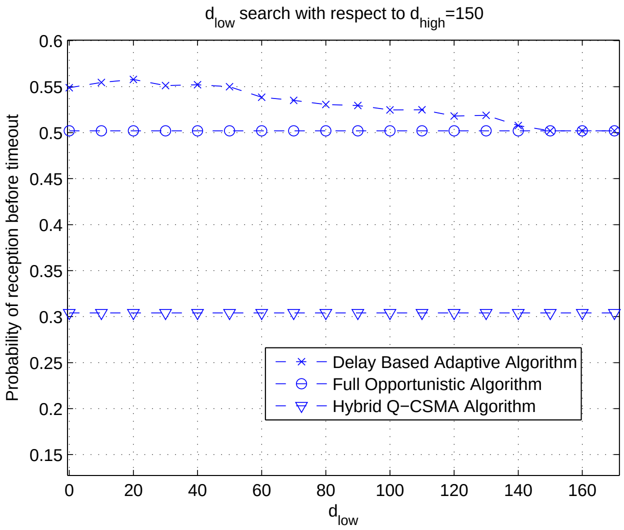


Figure 4.20: Probability of packets delivered before timeout vs. d_{low} in 24-link Grid Topology under 4-State CTMC Fading Radio Channel Model when $\rho = 0.72$

For the 24-link grid topology, when $\rho = 0.72$ and $d_{low} = 60$, probability of reception before timeout as a function d_{high} is shown in Figure 4.21.

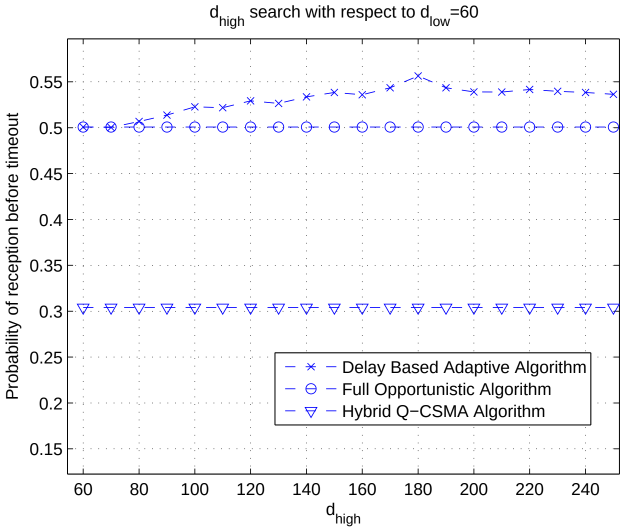


Figure 4.21: Probability of packets delivered before timeout vs. d_{high} in 24-link Grid Topology under 4-State CTMC Fading Radio Channel Model when $\rho = 0.72$

When the simulation results are analyzed, optimum values for d_{low} and d_{high} that work for all topologies and arrival rates do not exist. When $\rho = 0.6$, optimum d_{low} value with respect to $d_{high} = 150$ is found to be 10; however, when $\rho = 0.72$ optimum d_{low} value with respect to $d_{high} = 150$ is found to be 20. Even though, search is done using the same topology, with different arrival rates, optimum d_{low} values with respect to d_{high} values vary. In addition to this, when $\rho = 0.6$, if the probability of reception before timeout for $d_{low} = 20$ and $d_{high} = 150$ is compared with the probability of reception before timeout for $d_{low} = 60$ and $d_{high} = 190$, they are nearly equal. Similarly, when $\rho = 0.72$, if the probability of reception before timeout for $d_{low} = 10$ and $d_{high} = 150$ is compared with the probability of reception before timeout for $d_{low} = 60$ and $d_{high} = 180$, they are also nearly equal.

The good thing in the analysis is that, if d_{low} and d_{high} values are selected reasonably, the variation in the probability of transmission before timeout do not vary much. As a result, with the reasonable selection of parameters, a significant improvement over the Hybrid Q-CSMA algorithm is provided for a large range of values for the delay thresholds.

4.4.2 Delay Based Adaptive Algorithm with Delay Aware Transmitter

In delay aware systems, the receivers accept the packets transmitted if the delay is below the scheduled playout time for the packets. If one packet experiences timeout, even though it is transmitted, it will not be received by the receiver. As a result, by keeping that packet in the queue, the delays of the upcoming packets increase, which decreases the probability of reception before timeout for the upcoming packets. To prevent this, packets that experience timeout should be dropped without transmission. With this idea, all the algorithms are modified in a way that, if the delay of packets exceeds the scheduled playout time, they are dropped immediately at the transmitter side before transmission. As a result, probability of reception before timeout is increased.

Performance analysis are made for 24-link grid topology and 4-link line topology with the same parameters for the Hybrid Q-CSMA and the "Full Opportunistic Algorithm". For the "Delay Based Adaptive Algorithm", the threshold values are chosen as $d_{low} = 60$ slots and $d_{high} = 140$ slots. For all simulations, the scheduled playout time for packets is selected as 300 ms.

For the 24-link grid topology, probability of reception before timeout is plotted in Figure 4.22.

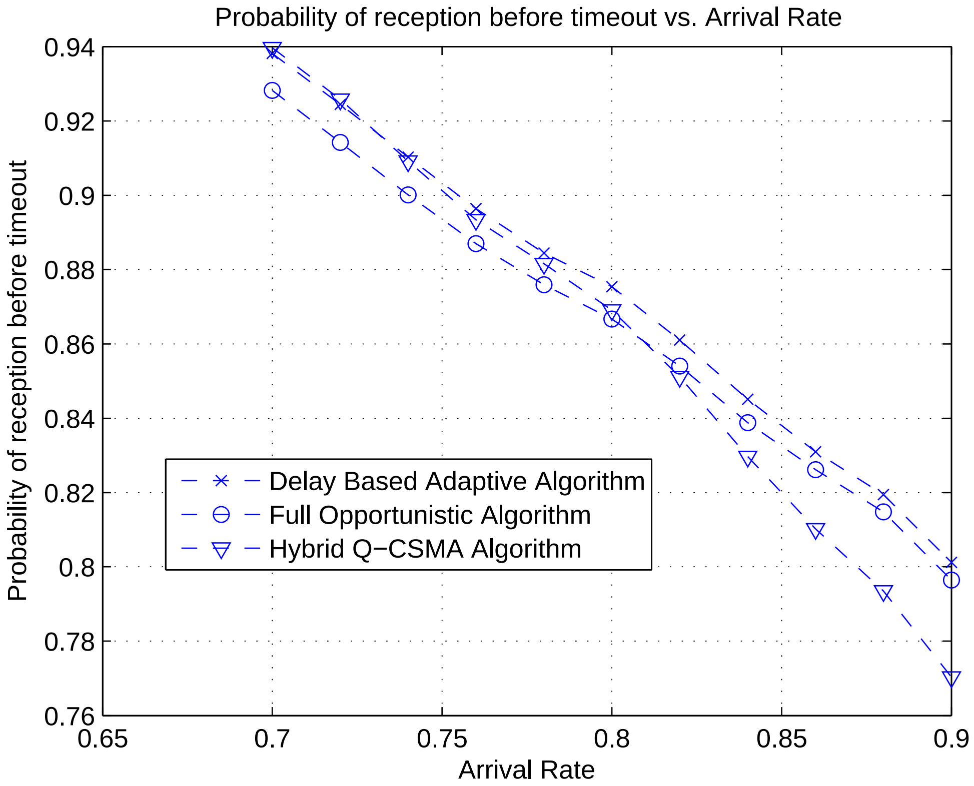


Figure 4.22: Probability of packets delivered before timeout vs. arrival rate for Delay Aware Systems in 24-link Grid Topology under 4-State CTMC Channel Model

For the 4-link line topology, probability of transmission before timeout is plotted in Figure 4.23.

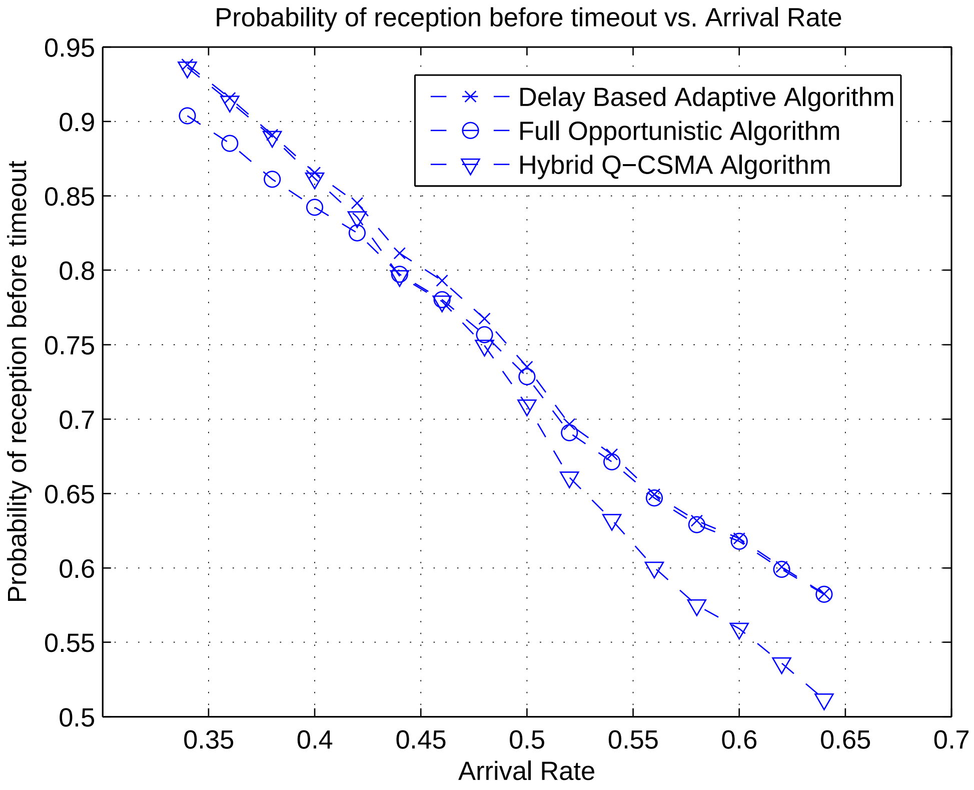


Figure 4.23: Probability of packets delivered before timeout vs. arrival rate for Delay Aware Systems in 4-link Line Topology under 4-State CTMC Channel Model

When the simulation results are observed, there is an important improvement in probability of reception before timeout when compared to delay unaware systems for all algorithms. We also observe that the "Delay Based Adaptive Algorithm" still outperforms the other two algorithms considered in this thesis.

Chapter 5

Conclusion

In this thesis, distributed, channel aware link scheduling problem is studied in wireless networks under time-varying fading radio channels. The main conclusion of this thesis is that, in addition to the average delay performances of the scheduling algorithms, maximum delay performances should be carefully analyzed for delay sensitive applications in which packets that are received after their scheduled playout time are useless. In this thesis, in order to analyze the probability of successful packet transmissions, a new metric "Effective Goodput" is introduced, which is the multiplication of the packet arrival rate with the probability of successful packet receptions before timeout.

The effective goodput performances of the distributed scheduling algorithms under time-varying fading radio channels are not satisfactory even though they are throughput optimum. When the transient behavior of distributed throughput optimum CSMA based link scheduling algorithms in the literature are analyzed, we observe that once any link is chosen in the transmission schedule, it takes time to deactivate that link. Link deactivation problem arises, when a link under fading is chosen in the transmission schedule. The data rate of the link under fading is relatively small so that when a link under fading is chosen in the transmission schedule, the data rate of the overall network decreases, up until the deactivation of that link. When the transient behavior of the distributed GMS algorithm is analyzed, deactivation of any link chosen is not difficult as in the case of Q-CSMA and Hybrid Q-CSMA algorithms. However, giving transmission opportunity to the links under fading, even for a short time, decreases the data rate of the overall network, which is inefficient. In order to overcome this problem, "Full Opportunistic Algorithm" is proposed, which does not give any transmission opportunity to the links under fading. Furthermore, in order to improve the effective goodput performance of the "Full Opportunistic Algorithm", "Delay Based Adaptive Algorithm" is proposed. "Delay Based Adaptive Algorithm" uses the advantages of both Hybrid Q-CSMA algorithm and "Full Opportunistic Algorithm" in order to increase the probability of successful packet receptions in the wireless network by decreasing the maximum delay of the links in the network. According to the performance analysis of the algorithms proposed, up to 100% performance improvement is achieved in terms of effective goodput. In addition, average delay is decreased by 20%. These results show that channel state awareness significantly improves the delay performance of the scheduling algorithms under time-varying fading radio channels.

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