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Load-regulated CSMA

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SUMMARY

In this paper, we derive throughput of a threshold-based transmission policy, namely load-regulated carrier sense multiple access (CSMA), taking into account the propagation delay of the medium and the offered load at different probabilities of the fading channel. In case of the saturated load-regulated CSMA, a trivial relationship between deterministic offered load to the channel at a particular fading channel condition and the maximum possible offered load has been shown. We further extend the load regulation concept into multi-channel domain. Both single and multi-channel load-regulated CSMA improves the throughput of the system compared with the existing CSMA system, which does not consider channel fading to control the packet transmissions. Copyright © 2008 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Medium access control (MAC) protocols for wireless communications have been widely studied. Analytical studies for carrier sense multiple access/collision avoidance (CSMA/CA) protocols and some simulation studies were accomplished in [1–3]. In [4], the throughput of CSMA/CA was calculated with a simple model in good channel condition. There are many studies for ALOHA family protocols in a fading channel and with shadowing [5–8]. However, the characteristics of the CSMA/CA cannot be described by ALOHA protocols and analytical framework of CSMA/CA has not yet been analyzed in a fading channel model. In [9], a Monte Carlo simulation-based approach was used to identify throughput of CSMA in fading channel. To cover fading effects, different channel models have been studied. Gilbert–Elliott model [10–12] focuses on describing channel error statistics. Several models have been proposed in terms of Rayleigh channels as in [13–16] where Markov process was applied for theoretical justification of fading effect.

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In [17], Qin and Berry considered an MAC protocol where each user possesses knowledge of its own channel gain. They introduced a channel-aware ALOHA where users can still exploit multi-user gains in a decentralized way. A series of related work were published in [18–20].

The gain in throughput observed in these channel state information (CSI) based MAC protocols is explained by two reasons: first, only a reduced number of nodes (those with good channel conditions) will be competing for the available bandwidth for a given time slot, which will reduce the number of collisions and second, the allowed transmissions will be successful with a higher probability due to the high signal quality that will reduce the number of retransmission requests, as well as the amount of bandwidth 'wasted' on unsuccessful transmissions. However, in a decentralized system, collisions can still occur unless CA mechanisms are implemented, resulting in an increased number of control packets and, therefore, drop in throughput performance.

In [21], the authors proposed a new time-asynchronous MAC paradigm- 'Channel MAC' which exploits the random nature of the channel fading characteristics to determine in a decentralized and distributed manner which node will access the channel at any given time. In contrast to [22], where user with the best channel is given access at a slot time, in Channel MAC, the channel of a user, which goes up the threshold first, is given access to the medium provided that no one else is transmitting. This opportunity persists until the channel gain goes down the threshold. In [23], the authors developed a similar threshold-based transmission policy (time-slotted, similar to [17]) where transmitters are active only if the channel to their receiver is acceptably strong. They obtained expressions for the optimal threshold and the capacity. This work, however, does not look into account the MAC transmission policy, e.g. distribution pattern of the (re-)transmission and relevant impact on throughput. Furthermore, none of the above work consider the unsaturated offered load condition in the analytical forms.

In this paper, we derive throughput of a threshold-based transmission policy, namely load-regulated CSMA from the offered load perspective and also taking into account the propagation delay of the medium and the fading channel. As a medium access mechanism we consider the non-persistant CSMA accompanied by the threshold-based transmission policy into our scheme. In non-persistent CSMA, a ready terminal senses the channel and if the channel is sensed idle, it transmits the packet. Otherwise, the terminal schedules the retransmission of the packet to some later time according to the retransmission delay distribution. This process is repeated until the packet is successfully transmitted. Hence, in the proposed load-regulated CSMA, a new packet transmission depends on the combined condition that (a) the medium is idle and (b) the corresponding predicted channel gain is above the threshold (i.e. the channel is in good state). The load-regulated CSMA is, therefore, a decentralized multiple access scheme governed by the channel estimation techniques. Multiple input multiple output (MIMO) technologies also rely on channel measurements for performance improvement. In MIMO systems, the space diversity, rather than the time diversity, is used to reduce the effect of channel fading. On the other hand, the multi-user diversity, motivated by the work of Knopp and Humblet [22], shows that scheduling the user with the best channel at any one time only maximizes the system capacity. Motivated by the multi-user diversity, the load-regulated CSMA performs the scheduling based on the underlying good channel condition, further to minimize the packet losses and maximize the throughput.

To the best of our knowledge, no work has considered the two parameters, offered load and propagation delay, with the channel fading probability to form an analytical expression for the threshold-based policy. We take into account those parameters in the analytical expressions. We later extend the load regulation concept into multi-channel domain. Both single and multi-channel load-regulated CSMA improves the throughput of the system as compared with the existing CSMA system.

The organization of the paper is as follows. In Section 2, the proposed load-regulated CSMA concept is described. In Section 3, the analytical framework for throughput estimation of non-persistent CSMA in fading channel is presented. We derive the analytical throughput equation of load-regulated non-persistent CSMA in Section 4. We investigate the load regulation concept in multi-channel CSMA case in Section 6 with improved throughput performance compared with the general multi-channel CSMA. Finally, Section 7 concludes the paper.

2. THE PROPOSED LOAD-REGULATED CSMA

The load-regulated CSMA predicts the channel state based on CSI and provides opportunistic data transmission depending on good channel state. We proceed with the following system model.

2.1. System model

2.1.1. Network model. Let us define a neighborhood of $2n$ nodes, where $N_T \in (1, 2, \ldots, n)$ are the transmitters and $N_R \in (1, 2, \ldots, n)$ are the receivers. For symmetry let us assume that each transmitter $i \in N_T$ is communicating with receiver $i \in N_R$. Therefore, we are considering a single-hop fully connected wireless scenario.

2.1.2. Channel model. We consider a simple two-state channel model. It has either a non-fade state (or good state), 'ON' with gain 1 or a fade state (bad state), 'OFF', with gain 0. The non-fade state persists with p probability. Hence, p can be defined as the probability of good channel. Only a packet sent at the good state is correctly received by the receiver.

Each packet transmission time is a constant l. Comparing it with the channel model, each 'ON' state is assumed to be constant l for simplicity. $g_{\max}$ is the maximum possible offered load to the channel by a single user when its corresponding channel is 100% good. Trivially, $g_{\max} = 1/l$ where $g_{\max}$ and l are represented in same time unit assuming same p probability of good channel condition for all the transmitter–receiver pairs. Hence, for n transmitter–receiver pairs, the maximum possible offered load $G_{\max}$ on the channel at $p(=1)$ prob. of good channel is

$$G_{\max} = g_{\max} \times n = \frac{1}{l} \times n \tag{1}$$

A trivial relationship between $G_{\max}$ and the offered load at different p probabilities of good channel, G_p is

$$G_p = \frac{p}{l} \times n = G_{\max} p \tag{2}$$

Therefore, we observe a deterministic offered load approach depending on p in the load-regulated CSMA.

2.1.3. Channel prediction. The load-regulated CSMA requires the nodes to predict the fading channel [24]. Fading generally occurs due to the multiple reflection of the transmitted signal from objects in the environment. If an unmodulated carrier at frequency f_c is transmitted over a fading

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channel, the complex envelope of the received noiseless signal is given by

$$c(t)=\sum_{n=1}^{N} A_n e^{j(2\pi f_n t+\theta_n)} \tag{3}$$

where N is the number of scatters, f_n is the Doppler frequency for the nth scatter and θ_n is the phase. The parameters A_n, f_n and θ_n vary slowly (on the order of 0.1 [25]) and can be viewed as fixed over a few milliseconds time-length [26]. This assumption provides the basis for channel predictions.

Most channel prediction methods in the literature can be broadly divided into three categories according to the underlying channel model: auto-regressive (AR), sum-of-sinusoids (SOS) and bandlimited process model-based algorithms [25]. To normalize the prediction range, it is often expressed in wavelengths, λ. When the maximum Doppler shift is f_d, a prediction t sec ahead corresponds to prediction of $f_d t$ wavelengths. Duel-Hallen *et al.* [25] and Semmelrodt and Kattenbach [27] provide overviews of long-range prediction techniques for fading channels, which include several techniques capable of predicting the channel over more than 1 wavelength.

In SOS model-based approach, if the parameters A_n, f_n and θ_n in Equation (3) remain fixed and are known perfectly, the individual complex sinusoids can be extrapolated and summed to produce reliable prediction of the fading signal. ESPIRIT is an example of SOS approach. The ESPRIT prediction scheme reliable prediction is feasible for about 1 wavelength [26]. At a speed of about 10 kmph, this corresponds to making predictions about 46 ms ahead at 2.4 GHz. Assuming that the ratio of power threshold to rms power of the envelop is 0.5 (i.e. $\rho=0.5$), level crossing rate (LCR) for the above parameters (i.e. speed = 10 kmph, frequency = 2.4 GHz) is about 35 crossing per second. This leads around 1.6 fades in 46 ms. Hence, with the ESPRIT scheme it is possible to predict the channel gain for the next 1 or 2 fading cycles. Furthermore, the modified covariance method discussed in [27] is capable of predicting the channel for up to 1.5 wavelengths. For the same parameters discussed above, this corresponds to predicting the channel gain for the next 2 to 3 fading cycles. The AR-model-based methods are more appropriate for realistic channels. The AR-model-based long-range prediction algorithm was discussed in [25]. In LRP, the low sampling rate increases the memory span and utilizes the large side-lobes of the channel autocorrelation function to predict the channel multiple of fading cycles (even larger than the channel coherence interval). For example, for the sampling frequency of 500 Hz and model order of 20, the memory span of channel prediction becomes 30 ms with almost accuracy, which represents 19k-step ahead of channel prediction.

However, the objective of this paper is to investigate whether a distributed access scheme given by the channel randomness can provide significant performance improvement. Hence, in this paper we do not suggest a particular prediction scheme to be used in conjunction with the load-regulated CSMA protocol. Based on the above cited literature [25, 26, 28], we assume that it is possible to accurately predict the channel fading for the next multiple number of fading cycles as required by the load-regulated CSMA protocol with a reasonable number of neighbors.[‡]

[‡] However, in practice, if the required prediction time-length is very large (in case of large number of users), either multi-step (predicting the full horizon in a single step) or iterated one-step predictions can be applied. Iterated one-step prediction is preferable in terms of calculation efficiency and accuracy in general time-dynamical system, although both procedures may suffer from the problem of exponential divergence. However, in large time distances, correlations in the samples becomes negligible. Mean value is the best prediction in this context, which results in minimal multi-step error. On the contrary, applying the false time dependance of the iterated prediction in this scenario may produce an average error of $\sqrt{2}$ the size of the multi-step error [29]. However, we do not consider this scalability problem in this paper.

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In short, node estimates the channel gain to the intended receiver. To estimate the channel a node requires a few samples of the channel gain [25]. This can be obtained through the received powers recorded on the acknowledgment packets or by sending periodic beacons[§] or a combination of both.[¶] Whenever a node needs to send a packet to a new node (i.e. start-up session of any new Tx–Rx pair), a series of beacon messages can be used to measure and predict the channel to the new node. In this paper, we assume that all channels are reciprocal due to the shorter communication range and the prediction algorithm is perfect due to the above discussion. In the result sections we analyze the effects of prediction errors on the system performance.

2.2. *Operation of load-regulated CSMA*

In non-persistent CSMA, a ready terminal senses the channel and if the channel is sensed idle, it transmits the packet. Otherwise, the terminal schedules the retransmission of the packet to some later time according to the retransmission delay distribution. This process is repeated until the packet is successfully transmitted. On the other hand, in the proposed load-regulated CSMA, a new packet transmission depends on the combined condition that (a) the medium is idle and (b) the corresponding predicted channel gain is above the threshold (i.e. the channel is in good state). Being a finite load system, idle time is evident here. We ignore the channel sensing delay for simplicity.

2.2.1. Admission control. Each transmitter possesses the knowledge of its channel gain. The offered load is sent or delayed to the channel according to its channel condition (i.e. good or bad channel). As soon as one packet arrives, it will be forwarded to the channel at the next available good peak such that its transmission is successful. This policy is equivalent to the scheme where the packet transmits exactly at the moment the packet arrives, given that the channel is good and the channel state persists until the packet transmission completes. Otherwise, the packet waits for the next threshold-crossing instant to transmit.

In either cases, transmission occurs only if no other node is transmitting at that time. This is the task of the load-controller within the MAC (Figure 1). It supports a large buffer to hold the packets before regulating the packets offered to the channel.

If the total offered load to the load-controllers, G is less than G_p for a particular probability of good channel (i.e. $G_p > G$), the load-controllers provide G load on the channel (because the channel can support it).

In case of $G \geqslant G_p$, the load-controllers offer only G_p to the channel. The rest of the packets are dropped.

2.2.2. Load arrival. The distribution of the arrival points of the load is assumed to be Poisson. Furthermore, the distribution of the load regulated from the load-controller to the channel is assumed to be Poisson for simplicity. However, the exact relationship of arrival point process is difficult to identify in this system. There is a dependency between an original arrival point of a packet and a retransmission point of the same packet, which invalidates the Poisson assumption.

[§] It may be a valid option only in unsaturated and/or slotted communication system of the load-regulated CSMA, which is a trivial extension of this paper. In this paper we mainly focus on the saturated time-asynchronous communication paradigm of load-regulated CSMA.

[¶] In case of saturated communication, non-periodic beacons can be sent to measure the channel.

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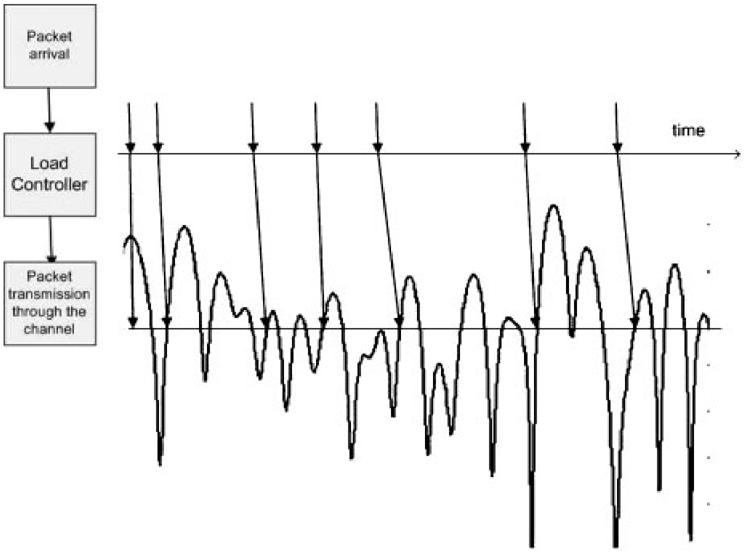

Figure 1. The load-regulated CSMA in operation.

However, if the retransmission schedule is uniformly chosen from an arbitrary large interval, the number of arrival points in any interval approaches to a Poisson distribution [30]. Furthermore, the superposition of independent and uniformly sparse processes converges to a Poisson process as the number of processes and the sparseness increase (i.e. no process dominates the others) [31]. The sparseness of the point processes is reflected by the fact that the occurrence of individual channels being good and corresponding packet transmission is almost random. Moreover, the Poisson assumption makes the analysis tractable.

2.2.3. Rate control. In this paper, we consider a single rate data transmission. However, a number of rate adaptive mechanisms [32–34] at the MAC layer have been proposed to exploit the multi-rate transmission capability based on the underlying channel conditions. Nonetheless, it is possible that the channel condition will significantly change during the single- [33] or multiple [34] packet transmission sequences of these protocols. If the transmission at the original rate is maintained (selected by RTS-CTS exchange trivially), error rates may become large if the channel quality worsens (packet losses), or the rate selection becomes sub-optimal if the channel quality improved during the cycle. Therefore, there is a possibility of further throughput improvement (i.e. decrease the packet loss or improve the sub-optimal to optimal rate selection) if the sender and receiver adapt the data rate during data transmissions. An improved distributed power control (DPC) algorithm was proposed in [35], where each MAC frames is adapted with the suitable power to maintain a target signal-to-interference ratio at the receiver. In the DPC algorithm, the time-varying fading channel for the next transmission is predicted to control the transmit power, which imposes more challenges in case of channel uncertainties. Both issues- (i) power control and (ii) auto rate adaptation, requiring to tackle the channel prediction challenges, results in a huge throughput improvements over the single rate IEEE 802.11 [36]. We intend to address the issue of rate and power adaptation scheme suitable for the 'load-regulated CSMA' in the future.

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3. ANALYTICAL MODEL OF NON-PERSISTENT CSMA IN FADING CHANNEL

The basic equation for the CSMA throughput S is defined in terms of a (the ratio of propagation delay to packet transmission time) and G (offered system load) in [1]. In the presence of fading we derive the throughput as

$$S=\frac{G\mathrm{e}^{-aG}(1-\pi_0)}{G(1+2a)+\mathrm{e}^{-aG}} \tag{4}$$

where π_0 is the probability of the bad channel due to fading.

Proof

Suppose λ is the arrival rate (i.e. offered system load). The probability that a transmission is successful in fading environment is equivalent to the combined probability that there is no other transmissions during the first a seconds of the period [1] and the designated transmission becomes successful with $(1-\pi_0)$ probability. Hence, the probability of the channel being used without any conflict is

$$\bar{U}=\mathrm{e}^{-\lambda t}\frac{(\lambda t)^0}{0!}(1-\pi_0)=\mathrm{e}^{-aG}(1-\pi_0) \quad (a\because t=a, \lambda=G) \tag{5}$$

Let $\bar{I}$ be the mean of idle time. Since, packet scheduling is memoryless,

$$\Pr[\bar{I}\leqslant x]=1-\Pr[\text{No packet scheduling during } x]=1-\mathrm{e}^{-Gx} \tag{6}$$

Hence, $\bar{I}$ is exponentially distributed with the mean of $1/G$.

Using the expected value of busy period (combination of both successful and unsuccessful transmission), successful transmission-period and idle period, we can formulate the throughput as follows:

$$S=\frac{\bar{U}}{\bar{B}+\bar{I}} \tag{7}$$

Suppose, the situation $Y\leqslant y$ implies the absence of arrival in the interval length of $a-y$.

The cumulative distribution function for Y is then

$$F_Y(y)=P(Y\leqslant y)=\mathrm{e}^{-G(a-y)} \quad (y\leqslant a) \tag{8}$$

$$\therefore P(y)=\frac{\mathrm{d}F_Y(y)}{\mathrm{d}y}=G\mathrm{e}^{-G(a-y)} \tag{9}$$

$$\therefore \bar{Y}=G\int_0^a y\mathrm{e}^{Gy-aG}\,\mathrm{d}y \tag{10}$$

$$\Longrightarrow \bar{Y}=a-\frac{1}{G}(1-\mathrm{e}^{-aG}) \tag{11}$$

Hence, we get the equation under fading conditions. □

Let $G=10, a=0.05$. Without considering fading, $S=0.5226$. In fading condition Equation (4) is applied. For $\pi_0=0.2$, $S=0.4181$; for $\pi_0=0.5, S=0.2613$. Therefore, throughput declines at fading conditions.

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4. LOAD-REGULATED CSMA IN FADING CHANNELS

If the total offered load on the load-controllers, G is less than G_p for a particular probability of good channel (i.e. $G_p > G$), the load-controller provides G load on the channel (because the channel can support it). The equation for the throughput S of load-regulated CSMA is equivalent to the general CSMA equation without packet-loss (due to properly load-forwarding) and is p-independent. In case of $G \geqslant G_p$, the load-controllers offer only G_p to the channel. The throughput equation of load-regulated CSMA in both cases can be represented as follows:

$$S = \begin{cases} \dfrac{G\mathrm{e}^{-aG}}{G(1+2a)+\mathrm{e}^{-aG}}, & G_p > G \\ \dfrac{G_{\max} p \mathrm{e}^{-aG_{\max} p}}{G_{\max} p(1+2a)+\mathrm{e}^{-aG_{\max} p}} & \text{otherwise} \end{cases} \tag{12}$$

Proof

Case $G \geqslant G_p$: After load regulation, the offered load is $G_p = G_{\max} p$. For simplicity we assume that there is a sufficient average non-fade duration (ANFD) of the channel so that the transmission of one packet can be completed successfully. Hence, the probability that a transmission is successful is equivalent to the scenario that there is no other transmissions during the first a seconds of the period. Hence, the probability of the channel being used without any conflict is

$$\bar{U} = \mathrm{e}^{-aG_{\max} p} \quad (\because t = a, \lambda = G_{\max} p) \tag{13}$$

Case $G < G_p$: Since the load-controller redirects the packets on the good channel, no packet-loss occurs. Therefore, the throughput equation is trivially equivalent to general CSMA equation with no packet loss.

Thus, we get the throughput equation of load-regulated CSMA. □

5. LOAD-REGULATED CSMA AT SATURATED LOAD CONDITION (WHEN $a = 0$)

At saturated load conditions, every node always has a packet ready to transmit. The offered load on the channel is determined by the load supported by the channel at a particular p-value of good channel. This situation is similar to our previously proposed Channel MAC paradigm [21]. In Channel MAC paradigm [21], an insignificant propagation delay is assumed in a typical ad hoc network scenario, which results in a negligible collision probability due to sensing delays. We assume every transmitter possesses p probability of good channel to the corresponding receiver. Suppose G is the maximum possible offered load from the load-controllers to the channel. It is equal to the summation of maximum possible LCRs of the channel for a fading distribution driven by the transmitter–receiver pairs. We assume that all the level-crossing points are distinct. In notation, $G = n \times \bar{R}$ where n is the number of transmitters and $\bar{R}$ is the maximum LCR value for a particular fading distribution.[‖] We assume that the level crossing points in the channel is Poisson for simplicity.

[‖] The offered load from the load-controllers to the channel cannot exceed G irrespective of the offered load from the upper layers to the load-controllers. We relate G to the distinct offered load to the channel at different good channel conditions and hence the term 'load regulation'.

We derive the throughput using two scenarios of channel models. We assume that each packet transmission time equals to a constant ANFD of the channel in both scenarios.

- *Scenario 1*: ANFD is constant irrespective of p and LCR is dependant on p (i.e. a particular statistical fading distribution).
- *Scenario 2*: Both ANFD and LCR are dependant on p.

5.1. Scenario 1

Suppose the ANFD of the channel is constant l. Since $p = \mathrm{LCR} \times \mathrm{ANFD}$, the offered load of 1 channel, $g = p/l$. Therefore, g increases as p increases.

5.1.1. Derivation. At $p = 1$, $g = 1/l$ attains maximum value (i.e. maximum offered load at $p = 1$ given $0 < l < 1$). Similarly, at $p_{0.5}$ (i.e. $p = 0.5$), corresponding offered load, $g_{0.5} = p_{0.5}/l = gp_{0.5}$.

Therefore, in general the offered load at p probability, $g_p = gp$, where g is the offered load of 1 user at 100% good channel. Accumulating all the offered load, we get the total offered load at p probability of good channel, $G_p = \sum_i gp = Gp$. By definition G is the total offered load at $p = 1$ in this scenario.

The packet transmission time is l. Hence, putting propagation delay, $a = 0$ in the general CSMA throughput equation [1] provided no packet is lost (due to the Channel MAC paradigm) at p probability of good channel is

$$S_p = \frac{l}{l + 1/Gp} \tag{14}$$

5.2. Scenario 2

We consider a Rayleigh fading channel. Both ANFD(l_p) and LCR (R_p) of the channels are equivalent to [37, Chapter 5]:

$$l_p = \frac{1}{\sqrt{2\pi} f_m \rho}, \quad R_p = \sqrt{2\pi} f_m \rho \mathrm{e}^{-\rho^2} \tag{15}$$

where f_m is the doppler frequency, ρ is the normalized threshold to the rms signal value (Figure 2) $p = \mathrm{e}^{-\rho^2}$. Hence, both ANFD and LCR are functions of p.

5.2.1. Derivation. The offered load $G_p = n \times R_p$. Following similar approach of Scenario 1, we get the throughput of the load-regulated CSMA as

$$S_p = \frac{l_p}{l_p + 1/G_p} \tag{16}$$

We observe that both Equations (14) and (16) are similar interpretations of the load-regulated CSMA. As $p = \mathrm{LCR} \times \mathrm{ANFD}$, both equations are equivalent to Equation (7). It can be trivially explained comparing Equation (14) with Equation (7), where l is a constant packet transmission time and G is the maximum possible offered load to the channel (i.e. summation of the maximum LCRs driven by the transmitter–receiver pairs at $p = 1$).

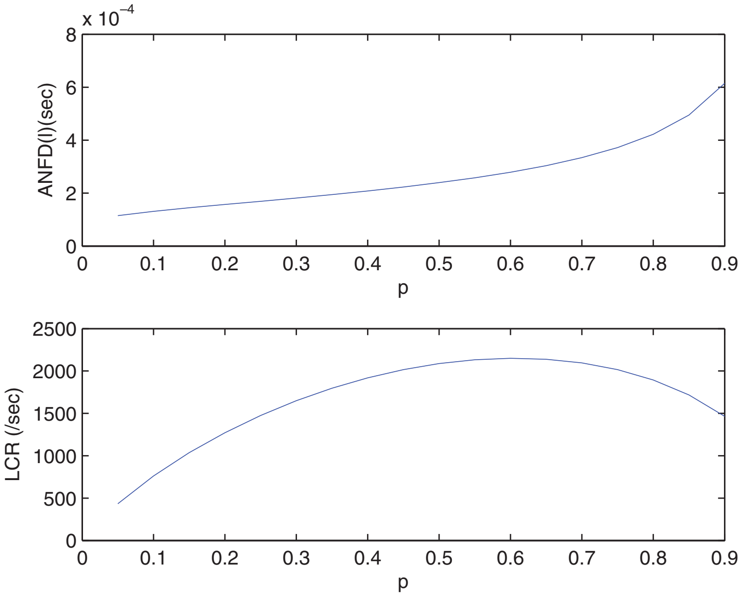

Figure 2. LCR and ANFD against p for Rayleigh fading channel with 2 GHz carrier frequency and 10 Kmph node-velocity (Scenario 2).

5.3. Simulation

We consider a single-hop communication system with slow fading channel for simulations. The Rayleigh distributed fading within a narrow-band signal envelop is generated according to the 'Dent model' proposed in [38]. p, which is equivalent to the probability that the channel gain H_i, is above a certain threshold, $H_{\hat{T}}$ is given by

$$p = \exp^{(-H_{\hat{T}}^2/h_0^2)} \tag{17}$$

where h_0 is the average value of fading.

In the simulation, for a given p-value we derive the channel gain threshold, $H_{\hat{T}}$. Then we generate a channel model, covering a time period $\hat{T}$, in the form of a set of time intervals where the channel gain is above the threshold $H_{\hat{T}}$ (assuming that the carrier frequency is 2 GHz and the node velocity is 10 kmph). These time periods are the transmission intervals of a node when the probability of good channel is p. For n nodes, n sets of independent $\mathbf{\Lambda}$ time intervals were generated. In case of overlapping transmission intervals from different nodes, only the first transmission interval in the overlapping group contributes to the throughput. Sensing and propagation delay for each node pair is set to 0.01% of corresponding transmission interval. A collision occurs if starting times of at least two transmissions are within 0.01% of each other. In case of a collision, transmission during the collision does not contribute to the throughput. By a Monte Carlo simulation we derive the throughput of the system over a number of simulation runs. We assume same p for all the stations in the simulation.

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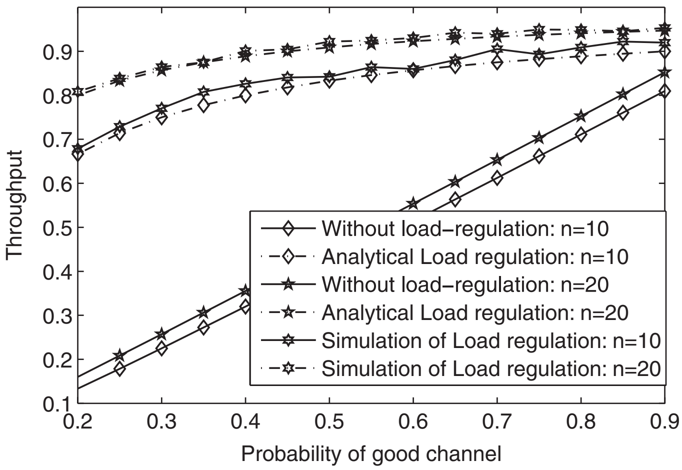

Figure 3. Throughput of saturated load-regulated CSMA in Rayleigh fading channels with $a = 0$.

For the analytical form of the load-regulated CSMA, we consider both l and LCR as a function of p as Equation (15) (Scenario 2). In Figure 3, we show the throughput performance of both cases. We observe a close correspondence between them.

5.3.1. Saturated load-regulated CSMA with $a > 0$. Following previous discussions of Scenario 2, the packet transmission time $l_p = \text{ANFD}$ of the channel $= f(p)$ and offered load, $G_p = n \times \text{LCR} = f(p)$.

Hence, the throughput equation of the load-regulated CSMA becomes

$$S_p = \frac{l_p G_p \mathrm{e}^{-aG_p}}{G_p(l_p + 2a) + \mathrm{e}^{-aG_p}} \tag{18}$$

Suppose $a = 0.01 \times l_p$ (normalized to l_p). The simulation scenario for the Rayleigh fading model is developed according to the previous section. In Figure 4, we observe both the analytical and simulation results match closely. Now collision increases for higher number of nodes due to the effect of propagation delay. In every case, the throughput of load-regulated CSMA outperforms the CSMA without load regulation.

5.3.2. Channel prediction inaccuracy. As we discussed earlier, in Rayleigh channels, we can predict the next received power value based on the past values. In [39], an AR prediction of slow Rayleigh fading channel is designed to improve the network performance of IEEE 802.11. An analysis on the accuracy of the prediction algorithm is shown there with the reasonably accurate simulation results. However, we use a simple model for prediction accuracy instead of the actual prediction algorithm similar to [40]. We define prediction accuracy as the percentage of predicted values within a fixed prediction range/horizon depending on system parameters (such as received SNR). Consistent with [39], we use a prediction accuracy of 90% in our simulation. In Figures 5 and 6, we show throughput degradation of the load-regulated CSMA considering different node

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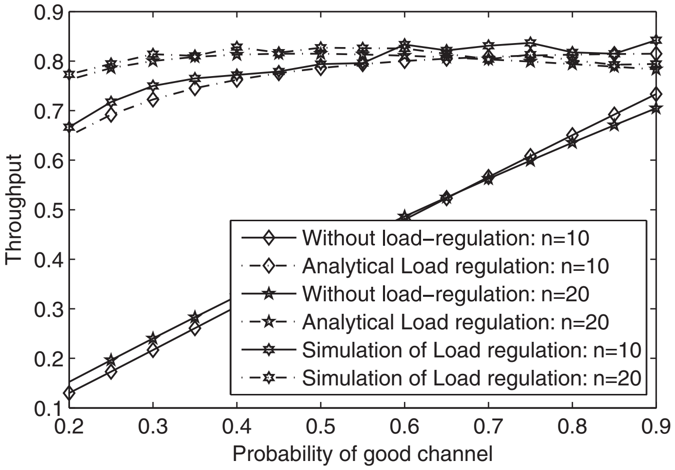

Figure 4. Throughput of saturated load-regulated CSMA in Rayleigh fading channels with $a = 0.01$ (normalized to packet transmission time).

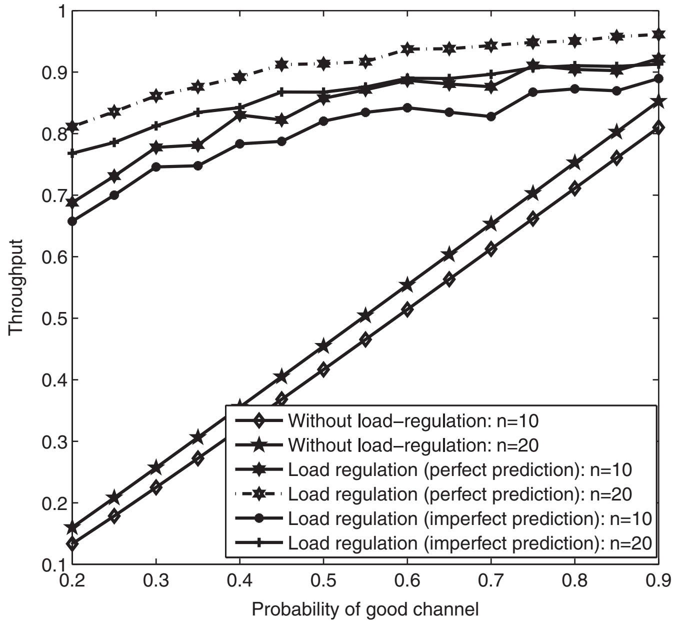

Figure 5. Throughput of saturated load-regulated CSMA in Rayleigh fading channels with $a = 0.00$ (normalized to packet transmission time) considering channel prediction inaccuracy.

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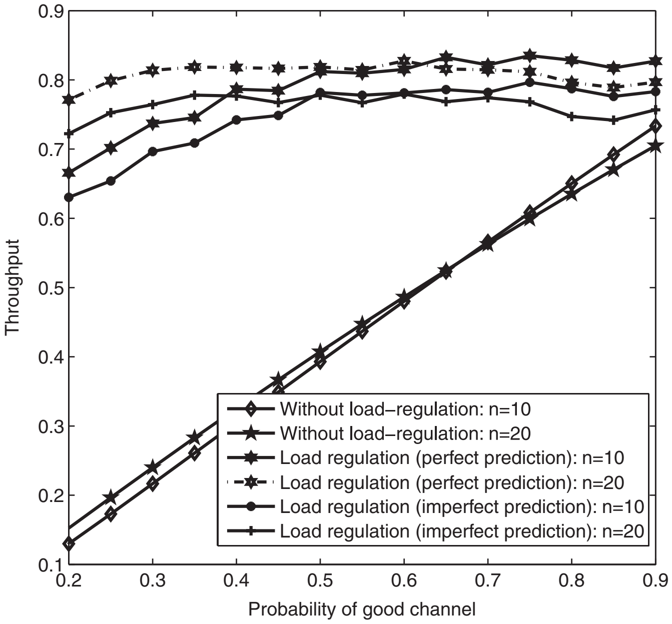

Figure 6. Throughput of saturated load-regulated CSMA in Rayleigh fading channels with $a = 0.01$ (normalized to packet transmission time) considering channel prediction inaccuracy.

numbers and a values. It is observed that the load-regulated CSMA still dominates over the CSMA without load regulation for all possible values of n and a in case of reasonable prediction inaccuracy.

6. LOAD REGULATION IN MULTI-CHANNEL MAC

A multi-channel network is made of a set of parallel channels. Ideally packet transmission time on each channel is inversely proportional to the bandwidth allocation to that channel.

If G is the offered load to the system, M is the number of parallel channels, a_0 is the normalized propagation delay for the total channel, from [41], we can state the following equation for multi-channel MAC:

$$S = \frac{G\mathrm{e}^{-a_0 G/M}}{G(2a_0/M + 1) + \mathrm{e}^{-a_0 G/M}} \tag{19}$$

which is the same relation that we obtain for CSMA with a single channel of bandwidth W and a propagation delay a_0/M.

In the following, we derive the analytical model of throughput equation of multi-channel CSMA-RC (random choice) in presence of fading.

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Suppose $i \in M$ channels are present, each channel is chosen with p_i probability. The throughput of channel i is obtained from the single channel expression of [1] by substituting G_i for G and a_i for a. The total throughput, S is then [41]:

$$S = G \sum_{i=1}^{M} \frac{p_i \mathrm{e}^{-a_i G W p_i / W_i} p}{G W p_i (2a_i + 1)/W_i + \mathrm{e}^{-a_i G W p_i / W_i}} \tag{20}$$

where W_i and W are the available bandwidth for ith channel and the total system, respectively, given the total system consists of i channels. Now we assume $W_i = W/M$, $a_i = a_0/M$ and $p_i = 1/M$ for symmetry. Hence

$$S = \frac{G \mathrm{e}^{-a_0 G/M} p}{G(2a_0/M + 1) + \mathrm{e}^{-a_0 G/M}} \tag{21}$$

Using Equation (21), we calculate throughput of multi-Channel MAC in the presence of fading. The results are: for $\pi_0 = 0.2$ and 0.5, throughput degrades to 0.6518 and 0.4074 (less than the ideal [non-fade assumption of the channel] throughput of 0.8148).

In load-regulated multi-channel CSMA case, we follow the similar discussion of Section 4. If the total offered load, G is less than the maximum possible offered load $G_{\max}$ at 100% good sub-channels with l packet-length, the throughput would be same as the throughput of multi-channel CSMA without packet-losses. Otherwise, maximum $G_{\max}$ load would go through the channel acted by the load-controllers. The relevant throughput at p probability of good sub-channels can be represented as:

$$S = \frac{G_{\max} p \mathrm{e}^{-a_0 G_{\max} p/M}}{G_{\max} p (2a_0/M + 1) + \mathrm{e}^{-a_0 G_{\max} p/M}} \tag{22}$$

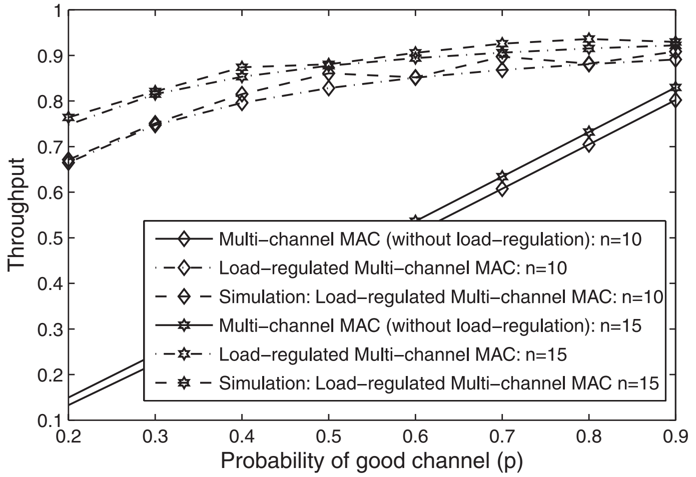

Figure 7. Throughput-p curve of saturated load-regulated multi-channel CSMA and general multi-channel CSMA with 10 and 15 channels; $a = 0.01 \times$ packet transmission time.

In Figure 7, throughput-p curve of saturated load-regulated multi-channel CSMA (both analytical and simulation) and general multi-channel CSMA with 10 and 15 channels are shown. The simulation setting for each channel is similar to the scenario described in Section 5.3. We ignore multi-channel co-ordination problems for simplicity. Owing to the load regulation, we observe improved throughput in the proposed system.

7. CONCLUSION

In this paper we present a mathematical throughput evaluation of load-regulated CSMA for fading channels. We concentrate on the analytical justification for using load-regulated CSMA in fading channels. Predicting the channel condition based on CSI and regulating the load into the channel accordingly has shown to improve the throughput in the presence of fading channels. This has been proved mathematically and using event-based simulations in this paper.

In the future we intend to further improve the system performance by introducing rate and power control. These techniques will allow optimum use of rate and power resources. Furthermore, in the context of multiple channels we will look at mechanisms for optimal scheduling of transmissions across all available channels, depending on the predicted channel conditions. Another area of future research will concentrate on proposing simple channel prediction techniques and analyzing the prediction errors of such schemes on the overall system performance.

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