On the Fairness and Stability of the Reverse-Link MAC Layer in cdma2000 1xEV-DO

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***Abstract*— We investigate the fairness of two reverse-link MAC algorithms in cdma2000 1xEV-DO High Rate Packet Data systems. Following the framework proposed by Kelly [5] for Internet congestion-control, we formulate a utility maximization problem and provide a simple sufficient condition for both algorithms to converge to the solution of this problem. Furthermore, we identify that the solution of this problem corresponds to the equal throughput fairness criteria, i.e., all the access terminals have equivalent throughput at the equilibrium.**

I. Introduction

The third generation (3G) wireless standard cdma2000 1xEV-DO, developed by Third Generation Partnership Project 2 (3GPP2), is designed in response to an increasing demand for high-speed wireless data service. The technology presents a breakthrough in providing very high data rate downstream Internet access to users. Meanwhile, the upstream traffic channel also has become increasingly important due to development of new applications, such as camera phones, interactive games and videoconferencing.

The reverse traffic channel of cdma2000 1xEV-DO system utilizes Code Division Multiple Access (CDMA) physical layer architecture to share the available bandwidth. On top of the physical layer, a medium access control (MAC) layer is utilized to provide an adaptive scheme to adjust the transmission rate of the access terminals (ATs) to fairly share and efficiently utilize the available bandwidth. A simple rate control scheme for the reverse traffic channel MAC is introduced in [1] and is adopted as a part of the IS-856 standard. Subsequently, an enhanced scheme [6] has been adopted for IS-856 Rev A to further improve the system efficiency. Both of these MAC algorithms can be viewed as distributed, feedback-based resource allocation schemes where the interference level at the basestation transceiver (BTS) is limited and the transmission rate at the ATs is adjusted in response to the interference level.

In this paper, we investigate the rate control algorithm of both [1] and [6] in the reverse traffic channel (upstream) of cdma2000 1xEV-DO system. As is always the case in any distributed resource allocation mechanism (for example, the TCP congestion-control mechanism in the Internet), the key properties of such schemes are *fairness* and *stability*. Here we consider the reverse traffic channel in an isolated sector where the ATs have full data buffer and are not power-limited. Under the utility maximization criterion in the framework proposed by Kelly [5], we identify the implicit utility functions of the rate control algorithms. Further, we provide a simple sufficient condition for both algorithms to be asymptotically stable and to converge to the fair rate allocation.

This paper is organized as follows. Section II presents simple models of the reverse traffic channel MAC algorithms. The utility maximization problem is formulated in Section III, and then the fairness and stability of the reverse traffic channel MAC algorithms are explored. Simulation results supporting the analysis are given in Section IV.

Some words on notation in use. The indicator function of an event A is given by $\mathbf{1}[A]$. For any $x, y, z \in \mathbb{R}$ and $y < z$, let $x \wedge y = \min(x, y)$, $x \vee y = \max(x, y)$ and $[x]_y^z = (x \wedge z) \vee y$, i.e., x is restricted to the range $[y, z]$.

II. The Reverse-Link MAC layer

In this section, we briefly describe the operation of the reverse traffic channel MAC layer in cdma2000 1xEV-DO system. The core of the reverse-link (RL) traffic channel is a distributed, feedback-based mechanism which can be separated into two components, i.e., the AT algorithm and the BTS algorithm. The AT algorithm autonomously adjusts each AT transmission rate/power according to the feedback signal from the BTS in order to maximize the throughput while keeping the interference level below a certain threshold.

We consider two RL MAC algorithms in this paper. First, we describe a simple model of the RL MAC algorithm in IS-856. Detailed description of the algorithm can be found in [1] and [9]. Later, a simplified model of the newly proposed *Enhanced* RL MAC algorithm [6] will be described.

Let N be the number of ATs that share the same BTS. Time is assumed to be slotted into contiguous timeslots. A timeslot is equal in duration to a subframe, which is the duration that each AT updates its transmission rate.

A. Access Terminal Model

For AT $i = 1, \ldots, N$, denote $R_i(t)$ as its transmission rate in timeslot $[t, t+1)$. Let $P_i(t)$ denote the current transmit pilot power of AT i in the timeslot. The pilot power $P_i(t)$ is controlled by the power control algorithm which tries to equalize the received pilot power from each AT at the BTS. Let $T_i(t)$ denote the ratio of the total transmit power to the pilot power (T2P) in linear scale of AT i in the timeslot $[t, t+1)$, i.e., the total transmit power of AT i in timeslot $[t, t+1)$ will be $T_i(t)P_i(t)$.

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1) IS-856 RL MAC: The set of permissible transmission rates in the IS-856 system is structured as $\mathcal{R} = \{0, R_{min}, 2R_{min}, \ldots, R_{max}/2, R_{max}\}$. In other words, for $n = 2, 3, \ldots$ the n-th member of the set has the value $2^{n-2}R_{min}$. In IS-856 system, $T_i(t)$ depends on the transmission rate, i.e.,

$$T_i(t) = F_R(R_i(t)), \tag{1}$$

for some $\mathcal{R} \to \mathcal{T}$ mapping F_R, where we denote the set of permissible T2P as $\mathcal{T} = \{1, T_{min}, \ldots, T_{max}\}$. Equivalently, we have the following relationship

$$R_i(t) = F_T(T_i(t)), \tag{2}$$

for some $\mathcal{T} \to \mathcal{R}$ mapping F_T. The sets $\mathcal{T}, \mathcal{R}$ and the mappings F_R, F_T depend on the physical layer of the system.

The transmission rate in the next timeslot of AT i depends on the marking mechanism at the BTS and its current transmission rate. The marking mechanism signals the ATs that the load level at the BTS exceeds the set threshold by setting the *Reverse Activity Bit (RAB)*. Each AT then responds through the following probabilistic algorithm. If RAB is set, AT i reduces the transmission rate in the next timeslot by half with probability $p(R_i(t))$ for some $\mathbb{R}_+ \to [0,1]$ mapping p. Otherwise, it retains its current transmission rate. On the other hand, if RAB is not set, AT i doubles its transmission rate in the next timeslot with probability $q(R_i(t))$ for some $\mathbb{R}_+ \to [0,1]$ mapping q or keeps its transmission rate the same otherwise. If we represent the RAB bit AT i received in the beginning timeslot $[t+1, t+2)$ by $M(t+1)$ (i.e., $M(t+1) = 1$ implies that the RAB bit is set in the beginning of timeslot $[t+1, t+2)$ and $M(t+1) = 0$ if not set), then the complete evolution of the transmission is

$$\begin{aligned} R_i(t+1) &= M(t+1)\mathbf{1}\left[U_i(t+1) \geq p(R_i(t))\right] R_i(t) \\ &+ M(t+1)\mathbf{1}\left[U_i(t+1) < p(R_i(t))\right]\left(\frac{R_i(t)}{2} \vee R_{min}\right) \\ &+ (1 - M(t+1))\mathbf{1}\left[U_i(t+1) < q(R_i(t))\right](2R_i(t) \wedge R_{max}) \\ &+ (1 - M(t+1))\mathbf{1}\left[U_i(t+1) \geq q(R_i(t))\right] R_i(t), \end{aligned}$$

where we let $\{U_i(t+1),\ i = 1, 2, \ldots, t = 0, 1, \ldots\}$ be a collection of $[0,1]$-uniform i.i.d. rvs.

2) Enhanced RL MAC: Enhanced RL MAC [6] adjusts and controls directly the AT transmit power instead of the transmission rate. This is done in part to improve the control of system loading and to adjust early termination goals in the hybrid ARQ.

Enhanced RL MAC also operates in a discrete-time fashion. For AT $i = 1, \ldots, N$, we still have a similar relationship between the transmission rate and power, i.e., $T_i(t) = F_R(R_i(t))$ for some $\mathcal{R} \to \mathcal{T}$ mapping F_R and $R_i(t) = F_T(T_i(t))$ for some $\mathcal{T} \to \mathcal{R}$ mapping F_T. The transmit power in the timeslot $[t+1, t+2)$ also responds to the RAB feedback information from the BTS algorithm similar to IS-856, however, there are now two rvs representing the transmit power: (i) the actual instantaneous transmission T2P $T_i(t+1)$ which is restricted to the discrete set $\mathcal{T}$ (ii) the allocated resource T2P $\hat{T}_i(t+1)$ which is an $\mathbb{R}$-valued continuous rv. Let $\Delta T_i(t+1)$ denote the difference in the allocated resource power between timeslot $[t, t+1)$ and $[t+1, t+2)$. Then

$$\hat{T}_i(t+1) = \left[\hat{T}_i(t) + \Delta T_i(t+1)\right]_{T_{min}}^{T_{max}} \tag{3}$$

$$\Delta T_i(t+1) = (1 - M(t+1))g_u(\hat{T}_i(t)) - M(t+1)g_d(\hat{T}_i(t)),$$

where g_u, g_d are some $\mathcal{T} \to \mathbb{R}_+$ mappings which control $\hat{T}$ ramping.

In order to determine the actual transmit power, a token bucket mechanism is utilized to map the continuous allocation $\hat{T}$ to the discrete allocation T. The token level $\beta_i(t)$ represents the available power budget that AT i can utilize at the end of the given timeslot $[t, t+1)$. After determining the proposed transmit power, the token level is filled by $\hat{T}_i(t+1)$. If we assume the ATs always transmit with the maximum allowable power, then

$$T_i(t+1) = \max_{t \in \mathcal{T}}\left(t \leq (\beta_i(t) + \hat{T}_i(t+1)) \wedge \beta_{max}\right),$$

where β_{max} is the token bucket size. After the transmission, the token level is drained by $T_i(t+1)$, the actual transmit power. So the token level at the end of the timeslot becomes

$$\beta_i(t+1) = (\beta_i(t) + \hat{T}_i(t+1)) \wedge \beta_{max} - T_i(t+1).$$

Note that $\beta_i(t) \geq 0$ for all $t = 1, 2, \ldots$.

In this manner, the variable T is chosen from a discrete set such that the average allocation matches that of the continuous variable $\hat{T}$, which is the resource allocated to the AT. The T value in effect dithers among discrete allocations to achieve the desired average power utilization.

B. Basestation Model

In each timeslot, the BTS receives the signal from all ATs. The accumulated power of the received signal is then used to calculate the *rise over thermal (RoT)* at the BTS, which represents the level of interference at the BTS. For proper system performance, the BTS needs to control the RoT to be below a certain threshold for the majority of timeslots, e.g., below 7 dB in 99% of the timeslots [2], to limit the level of interference while trying to maximize the throughput. In order to accomplish this, the BTS uses the aforementioned RAB bit to signal the ATs to reduce their transmission rate (or power) and hence reducing the RoT level. The RoT in timeslot $[t, t+1)$ is calculated as follows [7]:

$$Z(t) = 10 \log_{10}\left(1 + \sum_{i=1}^{N} \frac{T_i(t)P_R}{N_0 W}\right), \tag{4}$$

where $N_0 W$ represents the background noise power (including the intercell interference) in watts and we assume perfect power control, i.e., the pilot power from each AT at the BTS is exactly P_R watts – the power necessary for successful decoding.[1]

[1]In the actual system, the pilot power can fluctuate even with a perfect power control. However, such fluctuation is small when no single AT dominate the RoT at the BTS. Further discussion on this assumption is available in the appendix of [8].

The mechanism in which the BTS tries to control the RoT value to be under a certain threshold is by setting the RAB to signal the ATs to reduce the rate/power whenever the RoT exceeds the threshold, i.e.,

$$M(t+1) = \Gamma(Z(t)), \tag{5}$$

where $\Gamma : \mathbb{R}_+ \to \{0, 1\}$ is a step function with the threshold at Z_{thresh} dB.

III. Fairness and the Utility Maximization Model

We now consider the problem of allocating the total power to pilot ratio (T2P) T_i for each AT $i,\ i = 1, \ldots, N$ as a *competitive market* problem in economics in order to formulate the fairness criteria of the algorithm.

In our problem, each AT consumes a portion of the available interference power budget at the BTS. Since the acceptable interference level is limited, the BTS utilizes the RAB to signal the price of the resource to the ATs. In a competitive market, price is adjusted until the supply equals demand at which point the market is in equilibrium and the resulting allocation is *fair*. We use the utilitarian criterion (sometimes referred to as utility maximization), where the equilibrium (and fairness) is achieved for the allocation that results in the greatest sum of the utilities.

In this section, we first formulate a utility maximization problem following the framework proposed by Kelly [5] and later show that, under certain conditions, both of the RL MAC algorithms described in Section II approximate distributed algorithms which solve this utility maximization problem. Hence, both of the RL MAC algorithms are fair in the utilitarian criterion. Moreover, this fairness criteria is simple as each AT has equivalent throughput at the equilibrium.

A. The System Problem

For $i = 1, \ldots, N$, AT i has its own pilot channel, and its pilot power $P_i > 0$ is assumed to be perfectly controlled, i.e., the received pilot power at the BTS is equal to some constant P_R watts for each AT. The actual transmit power of AT i is determined by T2P factor $T_i > 0$ of the pilot power, i.e., the actual transmit power for AT i is $T_i P_i$. Here we assume that ATs are not power-limited.

The objective of the problem is to maximize the sum of the utility of the ATs which depends on T_i. Denote the utility function of AT i by $U_i : \mathbb{R}_+ \to \mathbb{R}$. The utility function U_i represents the consumer (or AT) preference or satisfaction towards the commodity (T_i). The consumer's satisfaction typically increases with diminishing return as the amount of the received commodity of the consumer increases.

Initially, we assume that U_i is increasing, differentiable and strictly concave. Further, we assume that the utility of AT i is equal to $U_i(T_i)$ with no regards to the actual transmit power. Under these assumptions, we can then derive the *fair* T2P allocations in Proposition 1 and Corollary 1 using a standard convex optimization technique. Then in Proposition 2, we derive the implicit utility functions associated with the distributed RL MAC algorithms and identify a simple condition which guarantees that the assumptions on the utility function in Proposition 1 and Corollary 1 are satisfied.

The maximization problem is constrained by the requirement that the rise-over-thermal (RoT) threshold, i.e., the interference level, is effectively restricted to be below a threshold Z_{thresh} dB. Let $N_0 W$ be the noise power in the system, then this constraint is equivalent to [7]:

$$10 \log_{10} \left(1 + \sum_{i=1}^{N} \frac{T_i P_R}{N_0 W} \right) \leq Z_{thresh}.$$

The objective of the problem is to maximize the sum of the utility. Therefore, we can pose the optimization problem as follows:

$$\max \sum_{i=1}^{N} U_i(T_i) \tag{6}$$

$$\text{subject to} \qquad \sum_{i=1}^{N} T_i \leq C \text{ and } T_i \geq 0,$$

where $C = \frac{N_0 W}{P_R}(10^{Z_{thresh}/10} - 1)$. We later refer to problem (6) as the *system* problem.

The first result follows from a straightforward convex optimization.

Proposition 1: Assuming $T_i \in \mathbb{R}_+,\ i = 1, \ldots, N$. Then the solution to the system problem satisfies $U'_k(T_k) = U'_l(T_l)$, $k, l = 1, 2, \ldots, N$.

The following result is a simple corollary of Proposition 1. It states that when the utility functions are uniform, then the fair rate allocation is the equal rate (or T2P) allocation.

Corollary 1: Assuming the condition in Proposition 1 with $U_1 = U_2 = \ldots = U_N$, then $T_k = T_l$ for $k, l = 1, \ldots, N$.

The optimization problem (6) is similar to the classic utility maximization problem considered by Kelly [5], which shows that the system problem can be decomposed into two separate problems, namely the *network* problem and the *users* problem, assuming the utility functions of the users are increasing and strictly concave. If the network maximizes its revenue in the network problem and then users subsequently maximize their utilities in the users problem, the recursive maximization sequences will converge to the solution of the system utility maximization problem. Subsequent work by Kelly et al. [4] shows that the system problem can be solved by a distributed algorithm. This distributed algorithm depends on the form of the utility function of the user. A more detailed summary of the framework is given in [8].

B. The Distributed Algorithm

We modify this distributed algorithm in a form suitable to our problem. Consider the following dynamical system:

$$\frac{dT_i}{dt} = k\left(T_i(t)\right) T_i(t) \left(U'_i(T_i(t)) - f\Big(\sum_{j=1}^{N} T_j(t)\Big) \right), \tag{7}$$

for $i = 1, \ldots, N$, where the penalty function $f : \mathbb{R}_+ \to \mathbb{R}_+$ is continuous, increasing and not identically zero. The mapping

$k : \mathbb{R}_+ \to (\epsilon, \infty)$ is a gain function for some fixed $\epsilon > 0$. It is easy to see that the dynamical system (7) tries to equalize $f\left(\sum_{j=1}^N T_j(t)\right)$ to $U_i'(T_i(t))$, i.e., at the equilibrium point we have $U_k'(T_k) = U_l'(T_l),\ k, l = 1, \ldots, N$ similar to Proposition 1.

Theorem 1 in [8] shows that the dynamical system (7) is asymptotically stable and converges to the solution of the approximated system problem, given that the utility function satisfies the aforementioned conditions, i.e., it is increasing, differentiable, and strictly concave.

In the discrete-time system of cdma2000 1xEV-DO, we can approximate the dynamic (7) as follows. Let $T_i(t)$ be the value of the transmit-to-pilot gain in timeslot t of AT i, then

$$T_i(t+1) - T_i(t) \approx k(T_i(t))T_i(t)[U_i'(T_i(t)) - f(\sum_{j=1}^N T_j(t))],$$

for $i = 1, \ldots, N$.

The penalty function f feeds the information of the state of the network, i.e., the RoT level back to the ATs. For f being a step function such as (5), the change in T_i can be written as follows:

$$\Delta T_i(t+1) = T_i(t+1) - T_i(t) \tag{8}$$
$$= \begin{cases} \Delta T_{up,i}(T_i(t)) := k(T_i(t))T_i(t)U_i'(T_i(t)) & \text{if } M(t+1) = 0 \\ \Delta T_{down,i}(T_i(t)) := k(T_i(t))T_i(t)\left(U_i'(T_i(t)) - 1\right) & \text{if } M(t+1) = 1, \end{cases}$$

where $M(t+1)$ is the *reverse activity bit* which will be set when the RoT rises above the set threshold of Z_{thresh} dB from (5). The following proposition shows the relationship between $\Delta T_{up,i}(T)$ and $\Delta T_{down,i}(T)$ and the implicit utility function U_i. Its proof is available in [8].

Proposition 2: Assume $\Delta T_{up}(T) > 0$ and $\Delta T_{down}(T) \leq 0$ for all $T > 0$. If the ratio $|\Delta T_{up}(T)/\Delta T_{down}(T)|$ is strictly decreasing as a function of T, then the RL MAC algorithm approximates a utility function which is increasing and strictly concave.

The approximated utility function is implicitly defined in the dynamic operation of the T ramping under RAB control. In the actual system, all the ATs use the same RL MAC algorithm, i.e., $\Delta T_{up,k}(T) = \Delta T_{up,l}(T)$ and $\Delta T_{down,k}(T) = \Delta T_{down,l}(T)$ for $T \in \mathbb{R}_+$ and $k, l = 1, \ldots, N$. This implies that all ATs have the same utility function. The following corollary follows from this observation, Corollary 1 and Proposition 2.

Corollary 2: Assuming conditions in Proposition 2 and $\Delta T_{up,k}(T) = \Delta T_{up,l}(T)$ and $\Delta T_{down,k}(T) = \Delta T_{down,l}(T)$ for $T \in \mathbb{R}_+$ and $k, l = 1, \ldots, N$, then the algorithm converges and at the equilibrium $T_k = T_l,\ k, l = 1, \ldots, N$.

C. Examples

For IS-856, we use the parameters given in Table 1 of [1] to approximate the value of $U'(T)$. Since the algorithm is probabilistic, we use the average increase/decrease of T instead, i.e., for any $R \in \mathcal{R}$

$$\begin{aligned} \Delta\bar{T}_{up}(F_R(R)) &= q(R)\left(F_R(2R \wedge R_{max}) - F_R(R)\right) \\ \Delta\bar{T}_{down}(F_R(R)) &= p(R)\left(F_R(\frac{R}{2} \vee R_{min}) - F_R(R)\right). \end{aligned}$$

The approximated value of $U'(T)$ is given in Table 1 in [8] which shows that $|\Delta\bar{T}_{up}(T)/\Delta\bar{T}_{down}(T)|$ is strictly decreasing in T. Therefore, we can conclude from Proposition 2 that U in the IS-856 system approximates an increasing and strictly concave function and thus at the equilibrium $T_k = T_l,\ k, l = 1, \ldots, N$ from Corollary 2.

For Enhanced RL MAC, we can deduce from (3) that $\Delta T_{up}(T) = g_u(T)$ and $\Delta T_{down}(T) = -g_d(T)$ for some $\mathbb{R}_+ \to \mathbb{R}_+$ mappings g_u, g_d. Since the functions g_u, g_d are always chosen such that the ratio $g_u(T)/g_d(T)$ is strictly decreasing in T [6], the conditions in Proposition 2 are satisfied trivially and the result from Corollary 2 immediately follows.

IV. Simulation Results

In this section, we present some simulation results supporting the theoretical findings in the previous section. According to Corollary 2, the distributed RL MAC algorithms are asymptotically stable and converge to the fair allocation under the condition that $|\Delta T_{up}(T)/\Delta T_{down}(T)|$ is strictly decreasing as a function of T. In this section, we simulate the RL MAC systems under this condition and demonstrate their fairness. Under the fairness criteria $T_k = T_l,\ k, l = 1, \ldots, N$, we can expect that the average throughput of the ATs are identical since the transmission rate of an AT is a function of T2P.

In order to quantify fairness under this criteria, we use the fairness index [3] which is given as $\frac{\left(\sum_{i=1}^N R_i\right)^2}{N \cdot \sum_{i=1}^N R_i^2}$, where N is the number of ATs in the sector and R_i is the average throughput of AT i. The range of the fairness index is $[0, 1]$. The fairer the throughputs are, the higher the index. The maximum value of the fairness index can be achieved if and only if $R_i = R_j,\ i, j = 1, \ldots, N$.

A. Simulator Description

In our simulator, a sector covers a hexagonal area. The access point contains two receive antennas which cover the sector. The simulation is performed on a single isolated sector. In the sector, ATs are randomly placed uniformly in the hexagonal area. The size of the sector is chosen according to a link budget that assumes the ATs are not power-limited, i.e., ATs always have enough power to transmit at their highest transmission rates R_{max}.

The simulator is discrete-time with the smallest time unit being a slot of $5/3$ ms. A packet on the reverse-link takes 16 slots to transmit irrespective of the transmission rate. The power control algorithm is enabled with the command being set every slot for IS-856 and every subframe (four slots) for Enhanced RL MAC. The power control command is assumed to be perfectly transmitted from the BTS to the ATs but is delayed by one slot in either case. Each AT increases (resp. decreases) its pilot power by 1 dB for every up (resp. down) power control command. The target pilot SINR is adjusted through the outer loop power control [9] to achieve 1% packet error rate.

We assume that the signal transmitted by each AT receives an independent fading, simulated by a single path Rayleigh fading process. The process is assumed to be exponentially correlated in time with correlation given as a function of the terminal's speed. In these simulations, we assume the terminal is moving at the speed of 3 km/h.

The simulation is performed under a snapshot mode, i.e., ATs location along with path loss and shadowing are fixed throughout the duration of the simulation. Since we assume the ATs are not power-limited, AT location has very little effect on MAC behavior. ATs are assumed to have full buffer, i.e., they transmit as much data as the MAC algorithm allows.

The RAB is generated at the BTS by comparing the RoT to the threshold. If the RoT is greater than the threshold at the BTS, then RAB is set to one. Otherwise, it is set to zero. The threshold level is dynamically adjusted to maintain that RoT exceeds the 7dB threshold less than 1% of the timeslots. The number of ATs in the sector is 16. The duration of the simulation is 300,000 timeslots.

1) IS-856: The transition probabilities of the probabilistic MAC algorithm are set according to the values given in [1]. In Section III-C, we have already demonstrated that these transition probabilities satisfy the conditions of Proposition 2.

The simulation result shows that the average AT throughput is 32.84 kbps while the standard deviation of the throughput is only 0.71 kbps. The fairness index of the throughput is 0.9996.

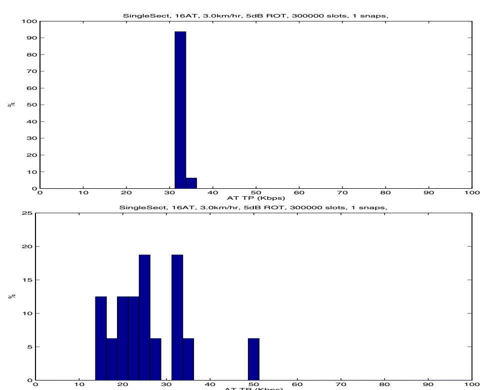

Fig. 1. Example of rate distribution in IS-856 RL MAC when (Top) the transition probabilities satisfy the conditions in Proposition 2, and (Bottom) the conditions in Proposition 2 are not satisfied.

We then simulate another system with the transition probabilities given in Table 2 in [8] which do not satisfy the condition in Proposition 2. For this system, the average AT throughput is reduced to 26.04 kbps while the standard deviation of the throughput is now 8.69 kbps. The fairness index of the throughput is now reduced to 0.9054. The comparison of the throughput distributions for the systems with these two different transition probabilities is shown in Figure 1.

2) Enhanced RL MAC: The simulation of Enhanced RL MAC is carried out over QUALCOMM's proprietary AT Class 7 specification. In this AT class, the function $g_u(.)$ and $g_d(.)$ in (3) are selected such that g_u/g_d is a strictly decreasing function. Therefore, the condition of Proposition 2 is trivially satisfied.

The result from the simulation shows that the average AT throughput is 57.03 kbps while the standard deviation of the throughput is 0.51 kbps. The fairness index of the throughput is 0.9999.

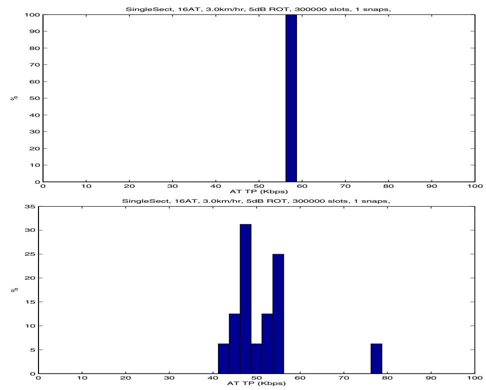

Fig. 2. Example of rate distribution in Enhanced RL MAC when (Top) the conditions of Proposition 2 are satisfied, and (Bottom) the conditions are not satisfied.

We also simulate Enhanced RL MAC with g_u, g_d selected such that the ratio $g_u/g_d = 1$ for all the values of T2P – this violates the sufficient conditions in Proposition 2. The average AT throughput is reduced to 51.21 kbps while the standard deviation of the throughput is 8.26 kbps. The fairness index of the throughput is 0.9762. The comparison of the throughput distribution between these two setups is shown in Figure 2.

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