Random-Access Scheduling with Service Differentiation in Wireless Networks

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***Abstract*— Recent years have seen tremendous growth in the deployment of Wireless Local Area Networks (WLANs). An important design issue in such networks is that of distributed scheduling. The lack of centralized control leads to multiple users competing for channel access. This leads to significant throughput degradation. Existing approaches, such as the slotted Aloha protocol and IEEE 802.11 DCF, also fail to provide differentiated service to users. The upcoming IEEE 802.11e Enhanced DCF incorporates additional mechanisms to provide support for service differentiation. However, the level of differentiation achieved with these mechanisms is difficult to quantify. In this paper, we propose a class of distributed scheduling algorithms, Regulated Contention Medium Access Control (RCMAC), which provides dynamic prioritized access to users for service differentiation in a quantifiable manner. Furthermore, by regulating multi-user contention, RCMAC achieves higher throughput when traffic is bursty, as is typically the case. In addition to WLANs, the basic concepts of RCMAC have applications in ad hoc networks and emerging sensor networks.**

I. INTRODUCTION

In recent years, there has been a surge in the popularity of Wireless Local Area Networks (WLANs) with extensive deployment all over the world. WLANs provide an effective means of achieving wireless data connectivity in offices, homes, campuses, supermarkets and other local environments and are expected to be an integral part of next-generation wireless communication networks.

An important design issue in WLANs is that of distributed scheduling. Unlike the cellular infrastructure, there is no central coordinating agent that controls the medium access of all WLAN terminals. Each terminal has to decide on its access strategy based on limited local information. This leads to multiple users competing for access to the shared channel, which results in collisions and decreases overall throughput. This loss in multi-user throughput is an inherent feature of well known distributed multi-access schemes like the slotted Aloha protocol [1] or its many variants [6] and IEEE 802.11 Distributed Coordination Function (DCF) [16]. The RTS/CTS handshake used in IEEE 802.11 DCF aims to counter this throughput loss by using large payloads and short control frames for channel reservation. However, in order to meet the tight service requirements of many applications, such as Voice over IP, it may often be necessary to send small packets, which will again reduce the system throughput efficiency significantly.

Furthermore, both the slotted Aloha and IEEE 802.11 DCF are incapable of distinguishing between service requirements. There is no separation between high and low priority flows, which results in equal competition for channel access. This leads to severe performance degradation in such environments of several multimedia applications, having tight bandwidth, delay and/or jitter requirements. The upcoming IEEE 802.11e Enhanced DCF (EDCF) [17] aims to address these issues by incorporating additional mechanisms to provide support for service differentiation. However, the level of differentiation achieved with these mechanisms is qualitative but difficult to quantify.

Our focus in this work is to alleviate the above shortcomings of existing MAC schemes with regard to both throughput constriction and service differentiation. We propose a class of distributed scheduling algorithms, Regulated Contention Medium Access Control (RCMAC), which improves throughput by reducing multi-user contention. RCMAC also provides dynamic prioritized access for service differentiation between users/flows in a quantifiable manner. RCMAC achieves this by sharing only two additional parameters, contention-level indicator and access threshold, in the contending neighborhood within the existing RTS/CTS handshake signaling mechanism. This is in contrast to many other proposals [9], [22], [31], [5], which either require additional signaling and/or more extensive exchange of state information, or are unable to provide adequate service differentiation. Further, it is worth noting that the basic principles of RCMAC can also be applied in a variety of other distributed wireless networking scenarios, including ad hoc and sensor networks.

The remainder of this paper is organized as follows. Two popular multi-access schemes, slotted Aloha and IEEE 802.11 MAC, are reviewed and their limitations identified in Section II. The proposed class of schemes, RCMAC, is presented in Section III. In Section IV, some analytical properties of the adaptation rule employed in RCMAC for estimating the contention level are discussed. In Section V, the 802.11 DCF window adaptation is analyzed under a fixed-point approximation. Results of simulations for performance

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comparison between RCMAC, slotted Aloha, and IEEE 802.11 are discussed in Section VI.

II. REVIEW OF EXISTING MAC SCHEMES

In this section, we review two popular distributed multi-access schemes: slotted Aloha and IEEE 802.11 MAC. We identify the main drawbacks and shortcomings of these access mechanisms, which will help motivate the need for RCMAC.

A. Slotted Aloha

Consider M transmitters trying to access a shared channel in order to communicate with a single receiver. Time is slotted with a possible data packet transmission over a single time slot. The shared medium is modeled as a collision channel, i.e., if two or more terminals attempt transmission in a single time slot, then all the attempting terminals are unsuccessful. Furthermore, all transmitters are assumed to receive $(0, 1, c)$ feedback at the end of each time slot, where 0 denotes an idle slot, 1 denotes a successful transmission and c denotes collision. Packets involved in a collision must be retransmitted in some later slot, with further such retransmissions until the packet is successfully received. Traditionally, slotted Aloha has been analyzed under the *no-buffering* and *infinite-user* models [11], [29], [6].

In the no-buffering model, if a node is currently waiting to transmit a packet or to retransmit a previously collided packet, all subsequent new arrivals at that node are discarded, until the successful transmission of the current packet. This assumption simplifies analysis by ignoring buffering effects. On the other hand, in the infinite-user model, every incoming packet is associated with a distinct virtual node, which transmits the packet in the next slot. Whenever a collision occurs in a slot, each virtual node (packet) involved in the collision is said to be backlogged and remains backlogged until it successfully transmits the packet. Each such backlogged node attempts to transmit the packet in each subsequent slot with some fixed probability, $p > 0$, independent of past slots and of other nodes. For this model, it has been shown that for any non-zero arrival rates such a system is unstable (that is the number of backlogged packets increases beyond bound). Nevertheless, if p is small, the onset of this undesirable behavior can be postponed. Furthermore, a number of distributed control approaches have been proposed [15], [29] that update the access probability p in each slot based on the (0,1,c)-feedback and are able to stabilize the system for arrivals with rate below $\frac{1}{e}$. Optimal centralized scheduling of packets achieves unit throughput. Clearly, there is a significant drop due to multi-user contention.

With regard to our present problem, a more insightful analysis would explicitly account for buffering at a finite set of terminals. However, the stability region of such a system, i.e., the set of vectors of arrival rates for which the queues are stable, is still unknown for arbitrary arrival statistics. Nevertheless, it is widely conjectured that the closure of the stability region, $\mathcal{C} \subset \Re_+^M$, is given by

$$\mathcal{C} = \left\{ vect\left(p_i \prod_{j \neq i} (1 - p_j) \right) : p_i \in [0, 1], 1 \leq i \leq M \right\}$$

where p_i denotes the access probability of terminal $i, i = 1, 2, \ldots, M$. The achievability of a rate vector in $\mathcal{C}^o$ has been known for stationary and independent arrivals as well as some non-stationary and non-independent arrival processes [28], [23], [26]. However, the converse, i.e., the non-achievability of a vector in the complement of $\mathcal{C}$, has been proved only for a specific model of the arrival process [3], where the total number of packets arriving in a time slot is geometrically distributed and each packet arrives at node i with a probability $\lambda_i / \sum_k \lambda_k$, independently of the others. Hence, the average arrival rate at node i is λ_i, but the arrival processes at different nodes are now dependent, unlike the standard independent arrivals model. The stability region is expected to be independent of the type of arrival process, though no formal proof is yet known.

For the special case of $M = 2$, the stability region can be obtained exactly and is shown in Fig. 1. Ideally, with centralized scheduling one can achieve unit sum rates for all arrival vectors. As seen in Fig. 1, the boundary of the slotted Aloha protocol falls well short of the idealized throughput. In fact, for symmetric arrivals, 2-user slotted Aloha throughput is at most half of the ideal throughput. This gap reduces with the skewing of arrival rates until slotted Aloha matches ideal performance when only one of the two users is active. Note that the boundary rates in Fig. 1 are themselves achieved only when the access probabilities are fixed a priori. This is rather unreasonable in practical scenarios where the number of active users and their arrival rates are dynamic. Hence, in practice, one suffers from even greater throughput degradations.

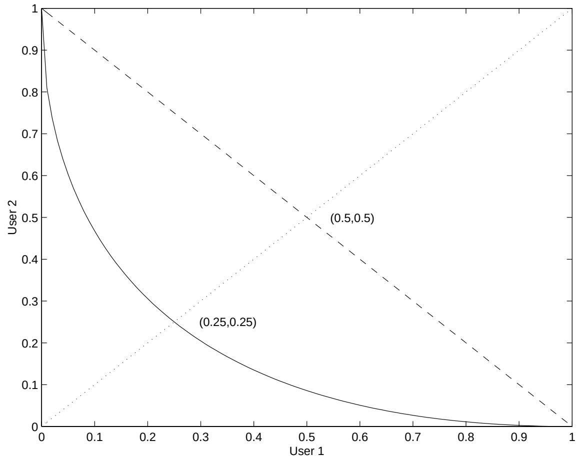

Fig. 1. Stability region of 2-user slotted Aloha.

A natural observation from Fig. 1 is that throughput enhancements in distributed multi-user environments are possible by operating at the extremes of the slotted Aloha boundary curve, i.e., as though the arrivals were skewed more than they actually are. In other words, by reducing competition between users, the overall throughput can be improved. This will be the central idea behind our proposed multi-access algorithm in Section III.

Before we discuss the IEEE 802.11 MAC next, we mention some more recent work on slotted Aloha [12], [13], [24], [20], [30], which study its performance in environments with *capture* effect, where the receiver can successfully decode one or more packets in a slot with some probability distribution.[1]

B. IEEE 802.11 MAC

The IEEE 802.11 WLAN standard defines two MAC functions, the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF).

DCF: The IEEE 802.11 DCF is a distributed multi-access mechanism based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and slotted Binary Exponential Backoff (BEB). A node with a pending transmission monitors the channel. If the channel is sensed idle for a period of time equal to the Distributed Inter Frame Spacing (DIFS), then the packet is transmitted (cf. Fig. 2). If the channel is sensed busy, the node continues to monitor the channel until it is idle for a DIFS. It then invokes the BEB procedure, whereby a random timer is chosen uniformly from a certain backoff window (W) size. The timer is decremented in slots as long as the channel is sensed idle and frozen as soon as the channel is sensed busy. Frozen timers are reactivated when the channel is again sensed idle for more than a DIFS. The node transmits when the timer expires. The BEB procedure doubles W after every unsuccessful transmission and drops down to a certain minimum backoff window, W_{min}, if the transmission was successful. (Later, in Section V, we will analyze the DCF window adaptation under a fixed-point approximation and will determine that the optimal incremental factor for W is in fact close to $e/(e-1) \approx 1.582$, instead of 2). Lastly, positive acknowledgments (ACKs) are sent upon each successful reception.

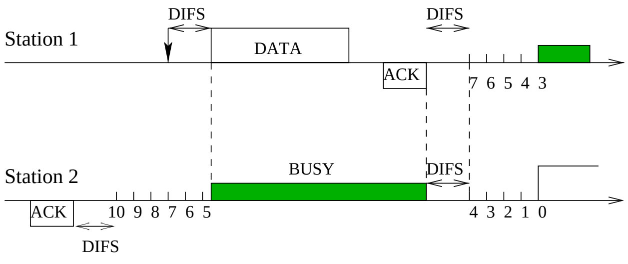

Fig. 2. IEEE 802.11 DCF operation.

The aforementioned CSMA/CA-based mechanism does not address the *hidden node* problem [27] (cf. Fig. 3). For this, IEEE 802.11 DCF – building upon the mechanism proposed in [18] and extended in [7] – provides for additional control signaling to inform the hidden nodes of the impending transmission: When a transmitter wants to send data to a node, it transmits a handshake signal, Request To Send (RTS); the intended receiver on correctly receiving RTS, responds with another handshake signal, Clear To Send (CTS). The RTS/CTS frames contain the source/destination IDs and the transmission duration. Neighbors of the transmitter hearing the RTS and DATA frames remain silent for the duration of the transmission by suitably updating their timers that indicate the channel-busy period, referred to as Network Allocation Vector (NAV). Hidden nodes hearing the CTS frame similarly suspend their transmissions for the duration of the DATA + ACK frames. The RTS/CTS signaling mechanism is illustrated in Fig. 4.

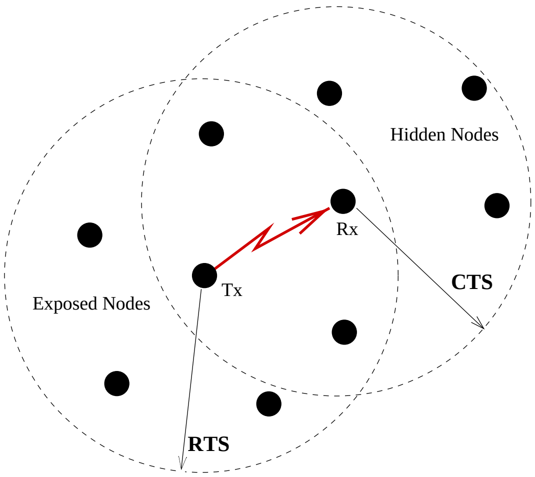

Fig. 3. RTS/CTS signaling to reserve channel prior to data transmission.

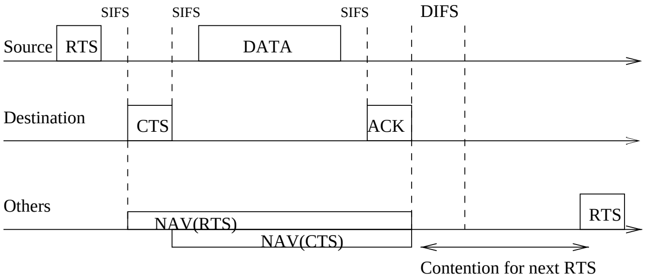

Fig. 4. DCF operation with RTS/CTS control signaling.

The RTS/CTS handshake can improve system throughput when large data frames are considered. Essentially, the short control signaling reserves the shared channel and allows a single user to subsequently transmit for long periods of time. This has the effect of pushing the operating point toward the extremes of the slotted Aloha boundary curve, as discussed in Section II-A. The important point to note however is that the RTS/CTS handshake merely reduces the length of the frames involved in contention and does not reduce multi-user contention as such. As will be seen in Section III, there is much to be gained by reducing contention between users.

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[1] We do not discuss them further as the emphasis here is more on how to provide service differentiation in a distributed environment—an issue that has not been adequately addressed even for the simpler model.

PCF: The PCF is an optional IEEE 802.11 MAC function designed to support time-bounded voice, audio and video services. It provides synchronous/contention free service, where the Access Point (AP) periodically polls each of the terminals for data packets. In a PCF-enabled WLAN, the two access methods PCF and DCF alternate, with a Contention-Free Period (CFP) followed by a Contention Period (CP). The transmission of a beacon signal signifies the start of a CFP where round-robin polling is normally used. Medium access during the CP follows the DCF outlined earlier. Fig. 5 illustrates the PCF mechanism.

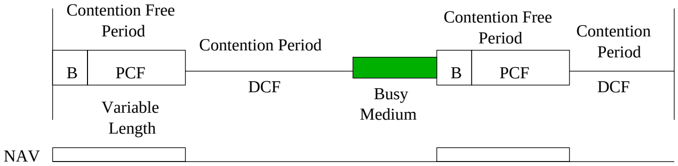

Fig. 5. IEEE 802.11 PCF operation.

Limitations of IEEE 802.11 MAC

- The IEEE 802.11 DCF can only support best effort services. High and low priority flows compete equally for channel access and hence the per-user throughput decreases with increasing number of active users. As a result, it is possible that high priority flows are starved. Clearly, such a scheme cannot provide the service differentiation needed for specified bandwidth, delay, and/or jitter in many multimedia applications.
- The IEEE 802.11 PCF was designed to support time bounded services, but the central polling mechanism is fairly complex and is only an optional function defined by the standard.[2] There is also considerable bandwidth expense in communicating through the AP each time rather than simple peer-to-peer communication. Furthermore, since the transmission time and data rates of a polled terminal are variable (as defined by standard), PCF may not be able to satisfy the service requirements of subsequently polled terminals.

802.11e EDCF: In order to address the above limitations of the IEEE 802.11 MAC functions, the emerging 802.11e standard [17] has proposals for the Enhanced Distributed Coordination Function (EDCF). EDCF provides a priority scheme by differentiating the minimum backoff window size (W_{min}) and Inter Frame Spacing, which is now termed as Arbitration IFS ($AIFS$). Specifically, each node implements up to 8 queues at the MAC layer to support 8 priority classes. Packets arriving from higher layers are assumed to be priority stamped and fall into the appropriate queue. Each of these queues then contends for channel access just as though it were another node, i.e., the queues behave as virtual terminals. Prioritization is achieved as follows: if priority of class i is greater than priority of class j, then $W^i_{min} \leq W^j_{min}$ and $AIFS^i \leq AIFS^j$ (cf. Fig. 6). If the back-off timers of two or more queues within a single terminal expire at the same time, then virtual collisions are avoided by granting the Transmission Opportunity (TXOP) to the highest priority queue. The lower priority queues then behave exactly as if there was an external collision on the channel.

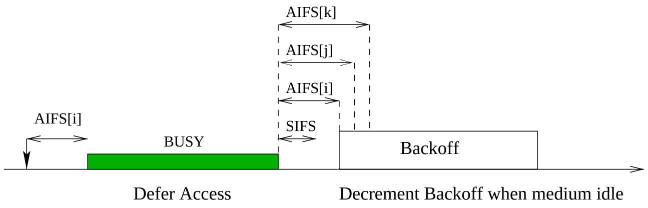

Fig. 6. IEEE 802.11 EDCF operation.

Although the proposed IEEE 802.11e EDCF differentiates services by providing up to 8 priority classes, it has the following shortcomings:

- EDCF only intends to resolve contention across priority classes. Hence, high-priority traffic at different nodes continue to compete with each other.
- Even internal to a single node, a high-priority flow may not always get to transmit before a lower-priority flow with EDCF. (This is so because different priority queues within a node backoff randomly and independently and TXOP only resolves internal collisions but does not prevent a lower-priority flow from accessing the channel first if its backoff timer expires before that of a higher-priority flow with a larger (random) value.)
- In several applications, dynamic service differentiation may be required. For instance, the total available bandwidth may need to be allocated in a certain proportion among the users. Even though EDCF provides support for service differentiation, through variable AIFS and minimum backoff window size mechanisms, it is qualitative but difficult to quantify (i.e., it is not clear how to set these parameters to achieve a given objective, for instance, the aforementioned allocating the available throughput in a certain proportion among the users).

III. REGULATED CONTENTION MEDIUM ACCESS CONTROL (RCMAC)

From our previous discussions on the slotted Aloha and IEEE 802.11 MAC, we can identify two important issues that need to be addressed for distributed scheduling:

1) Effective regulation of multi-user contention for shared channel access to improve total throughput,
2) Dynamic prioritized access to users for each transmission depending on the service requirements.

We next propose a class of distributed algorithms, Regulated Contention Medium Access Control (RCMAC), which aims at addressing the above issues. Rather than transfer multi-user contention to the short signaling phase (as in the RTS/CTS

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[2] PCF functionality is not implemented in most current IEEE 802.11-based systems.

handshake), RCMAC reduces multi-user contention by allowing only a subset of the active nodes to attempt channel access. This yields significant throughput improvements over both slotted Aloha and IEEE 802.11 DCF when traffic is bursty. By regulating multi-user contention in a controlled fashion, RCMAC also provides dynamic service differentiation in a quantifiable manner, unlike in IEEE 802.11e.

A. RCMAC: Definition

Consider the setup of slotted Aloha, as discussed in Section II-A, with the difference that the users' access probabilities $p_i, i = 1, 2, \ldots, M$, in a slot are not fixed, but rather are dynamic, depending on the users' own states and some system-wide variables shared among contending users. More specifically, each user maintains variable $q_i = q_i(t)$, which is its *dynamic weight*; some example choices for dynamic weight are the queue length or the delay/age of the "oldest" packet. User i sets its access probability in a slot t to be

$$p_i = \min\left\{\frac{f(q_i, \tau)}{W}, 1\right\} \ , \tag{1}$$

where f is some fixed function, $\tau = \tau(t)$ is *access threshold* and $W = W(t)$ is *contention level*, which are shared among users in the contending neighborhood (in the way we describe below). Typically, access threshold τ will be the weight q_i of the user i with most recent successful transmission. The function $f(.)$ serves to differentiate access probabilities of users with different weights q_i. For instance, as we will discuss in detail later, f may be chosen so that the users with q_i below τ may be temporarily banned from accessing the channel. The contention level W is dynamically adjusted in a way so as to maximize the total channel throughput. This is achieved by *approximately* maintaining the equality (justification for which is provided later in Proposition 2)

$$\sum_i p_i = 1 \ . \tag{2}$$

Remark 1: Access mechanism described above is quite general. For example, when $f(\cdot) \equiv 1$, which corresponds to the case when we do not want to provide any service differentiation between users, the desired value of W would simply be the number of active users M. This will result in all $p_i \approx 1/M$, and thus, in this case, RCMAC will emulate slotted Aloha, with the user access probabilities set to achieve optimal system throughput.

Remark 2: The general approach of making users' relative channel access priorities dependent on their dynamic weights q_i is similar to that used in some centralized wireless scheduling schemes ([4], [25] and references therein). The meaning and specific choices of q_i can also be similar. We emphasize, however, that the key feature of our scheme is that it is *decentralized*: contending users need *not* know exact values of dynamic weights of all other users.
We next discuss an algorithm for adapting the measure of contention level W.

B. Contention Level Adaptation

We employ the Multiplicative Increase/Decrease (MID) rule for updating the contention level W. Specifically, $W(t)$ is multiplicatively increased by a factor of $(1+u)$, $u > 0$, after every collision on the channel and multiplicatively decreased by a factor of $(1-d)$, $d > 0$, after every successful transmission on the channel. In addition, after every successful transmission, the current value of $\max\{W(t), f(q_i, \tau)\}$ of the successful transmitter i is copied as the new value of $W(t)$ by all users. (This can be achieved, for instance, by incorporating a field for W within the RTS/CTS signaling framework of IEEE 802.11.)

Remark 3: The MID adaptation rule is in contrast to the backoff update policy used in 802.11 DCF, where backoff window, W, is reduced to W_{min} after every successful transmission. It has been shown in [8] that the optimal W_{min} that maximizes throughput is a function of the number of current active users. However, in the current 802.11 standard, the value of W_{min} is hard wired and cannot be adapted. On the other hand, the proposal for Multiplicative Increase Linear Decrease (MILD) [7] is too conservative on decrease and leads to unwanted idling, which again reduces throughput. By employing the MID rule in RCMAC, we reach a *middle* ground between the "collapsing" decrease of W in DCF and the "conservative" decrease of W in MILD.

In the sequel (Section IV), we will analyze the MID rule to indicate its desirable behavior, as well as provide good choices for parameters u and d.

C. Access Threshold and Differentiation Function

Here we discuss how in (1) the access threshold τ and limiting function $f(\cdot)$ are chosen.

First consider the access threshold τ. Just as with W, after every successful transmission, the current value of dynamic weight $q_i(t)$ of the successful transmitter i is copied as the new value of the access threshold $\tau(t)$ by all users. A natural choice for dynamic weight q_i (which also will be used in the simulation experiments discussed in the sequel) is simply the queue length of user i (either the actual number of packets, or the length of a virtual token queue). It can, however, be a more general measure of user i's *dynamic* urgency or priority. Later in Section VI we will discuss one such specific measure for providing throughput sharing among users akin to the generalized process sharing discipline [21].

For the differentiation function, $f(q_i, \tau)$, which determines the relative values of the access probabilities of users, we consider two special cases in this paper.

The first option is $f(q_i, \tau) = q_i/\tau$, in which case p_i's are simply proportional to q_i. We refer to this version as *weight proportional* (WP). (Note that τ here plays no essential role – it serves only for normalization.)

The second option, which we call *threshold based regulation* (TBR), is such that $f(q_i, \tau) = I\{q_i \geq \tau\}$, where $I\{\cdot\}$ is the indicator function.

IV. ANALYSIS OF MID ADAPTATION RULE

We next obtain some analytical properties of the MID rule. We start with some notation. Let $p = p(t) = (p_1, \dots, p_M)$ be the vector of user access probabilities in slot t. Further, denote the system total throughput corresponding to fixed p by

$$\mu = \mu(p) = \sum_{i=1}^{M} \left(p_i \prod_{j \neq i} (1 - p_j) \right) \ , \tag{3}$$

and the conditional success probability, under the condition of at least one access attempt in a slot, by

$$s = s(p) = \frac{\sum_{i=1}^{M} \left(p_i \prod_{j \neq i} (1 - p_j) \right)}{1 - \prod_{i=1}^{M} (1 - p_i)} \ . \tag{4}$$

The following monotonicity property is very intuitive.

Lemma 1: The function $s = s(p)$ is non-increasing on each $p_i \in [0,1]$. Moreover, in the non-degenerate case $M \geq 2$, $s(p)$ is strictly decreasing on p_i at any point p such that $p_j > 0$ for at least one $j \neq i$ and $p_j = 1$ for no more than one $j \neq i$.

Proof: In the degenerate case $M = 1$, $s(p) = s(p_1) = 1$ for any $p_1 > 0$. Let us consider the case $M \geq 2$ and, without loss of generality, let $i = 1$. Note that $s(p)$ in (4) can be written as

$$s(p) = \frac{\mu(p)}{\nu(p)},$$

where $\mu(p)$, defined in (3), is interpreted as the probability that *exactly one* user makes a transmission attempt in a slot, and

$$\nu(p) = 1 - \prod_{j=1}^{M} (1 - p_j)$$

is the probability that *at least one* user attempts in a slot. We can rewrite $s(p)$ as follows:

$$s(p) = \frac{p_1(1 - \nu_1) + (1 - p_1)\mu_1}{p_1 + (1 - p_1)\nu_1} \ , \tag{5}$$

where $\mu_1 = \mu_1(p_2, \dots, p_M)$ and $\nu_1 = \nu_1(p_2, \dots, p_M)$ have the same meaning as $\mu(p)$ and $\nu(p)$, respectively, but with user 1 excluded from the set of users competing for a slot. Taking partial derivative of $s(p)$ on p_1 we obtain (after some algebra):

$$\frac{\partial}{\partial p_1} s(p) = \frac{(\nu_1 - \mu_1) - \nu_1^2}{[p_1 + (1 - p_1)\nu_1]^2} \ . \tag{6}$$

Consider a system with users $2, \dots, M$ (but not user 1) competing for time slots. In such a system, $(\nu_1 - \mu_1)$ is the probability that at least two different users attempt in a single slot, and ν_1^2 is the probability that at least one user attempts in each of two fixed different slots. This interpretation shows that we always have

$$(\nu_1 - \mu_1) \leq \nu_1^2,$$

and, moreover, the above inequality is strict under the additional condition on p specified in the statement of the lemma. ■

To illustrate some basic properties of the MID rule for W updates, as well as to motivate the choice of the parameters u and d, consider the following simple model. Suppose that the values of $f(q_i, \tau) =: \phi_i$ do not change in time, and assume that at least one $\phi_i > 0$. (Below we denote $\bar{\phi} \doteq \max_i \phi_i$.) The following result justifies the "fixed point" approximation of the "stable" value of W resulting from the MID rule.

Theorem 1: There exists a unique value W_* such that, for $p_i = \phi_i / W$ with $W = W_*$, either

$$\max_i p_i < 1 \ \text{ and } \ (1 + u)^{(1-s)}(1 - d)^s = 1 \ , \tag{7}$$

or

$$\max_i p_i = 1 \ \text{ and } \ (1 + u)^{(1-s)}(1 - d)^s \leq 1 \ . \tag{8}$$

Proof: Denote $y = (1+u)^{(1-s)}(1-d)^s$, which, under the assumptions of the proposition, is a function of W only. In the degenerate case $M = 1$, we have $s = 1$ for any $p_1 \in (0, 1]$ or, equivalently, for any $W \in [\phi_1, \infty)$. Therefore, $y = 1 - d < 1$ for any $W \in [\phi_1, \infty)$. Obviously, $W_* = \phi_1$ is the only W_* satisfying (8), and no W_* satisfies (7).

In the non-degenerate case $M \geq 2$, if we decrease W continuously from $+\infty$, then each p_i monotonically and continuously (strictly) increases. Consequently, by Lemma 1, s monotonically and continuously (strictly) decreases from initial value 1, and therefore y monotonically and continuously (strictly) increases from initial value $1 - d$. It is easy to see that the value of W at which either y hits 1 or W hits $\bar{\phi}$ is the unique W_* satisfying either (7) or (8). ■

Theorem 1 reflects the simple fact that, if $W(t)$ were to "stabilize" around some value W_*, this W_* must satisfy a "zero average drift" condition. If W_* satisfies $\max_i p_i < 1$ (a more generic case), then the drift condition is as in (7); otherwise, when $\max_i p_i = 1$, or equivalently $W_* = \bar{\phi}$, the drift condition needs to be relaxed to the one in (8), because in this case it is possible (and typical) that $W(t)$ has (potentially) negative drift at W_*, but is "stable" because it is "pushed against the floor" $\bar{\phi}$.

It is easy to see that the fixed point approximation for W, described in Theorem 1, is in fact *asymptotically exact* when both u and d are small. Indeed, consider the asymptotic regime such that $u = \epsilon \hat{u} > 0$ and $d = \epsilon \hat{d} > 0$, where $\hat{u} > 0$ and $\hat{d} > 0$ are fixed constants and parameter $\epsilon \downarrow 0$. First, we observe that as $\epsilon \downarrow 0$, $W_* \to W_{**}$, where W_{**} is the minimum of all W such that $W \geq \bar{\phi}$ and $(1 - s)\hat{u} - s\hat{d} \leq 0$. (Here s is a function of W, via p.) Then, the following proposition holds.

Proposition 1: (i) For each $\epsilon > 0$, consider the random process $W^{(\epsilon)}(t) \doteq W(\lfloor t/\epsilon \rfloor)$ in continuous time $t \geq 0$. Suppose $W^{(\epsilon)}(0) \to w(0)$. Then, as $\epsilon \to 0$, the process $W^{(\epsilon)}(t), t \geq 0$, converges to the deterministic process $w(t)$ (with initial state $w(0)$), satisfying differential equation

$$\frac{d}{dt} (\log w) = \nu \left((1 - s)\hat{u} - s\hat{d} \right) , \quad \bar{\phi} < w < \infty,$$

and, at the boundary,

$$\frac{d^+}{dt} (\log w) = \max \left\{ 0, \, \nu \left((1 - s)\hat{u} - s\hat{d} \right) \right\} , \quad w = \bar{\phi},$$

where s and ν are functions of w (via p), as specified earlier, and d^+/dt denotes right derivative. The convergence is in the sense that, for any $T > 0$,

$$\max_{t\in[0,T]} \left| W^{(\epsilon)}(t) - w(t) \right| \xrightarrow{P} 0 \ .$$

(ii) For any $w(0)$, $w(t) \to W_{**}$ as $t \to \infty$.

Proof: (i) This convergence is a standard "hydrodynamic" or "law-of-large-numbers" limit result; we do not provide proof details – cf. Section 11.2 of [10] for results of this type. Uniqueness of the deterministic process $w(t),\ t \geq 0$, solving the differential equation is verified directly.
(ii) The derivative $\frac{d}{dt}(\log w)$ is strictly negative when $w(t) > W_{**}$ and strictly positive when $w(t) < W_{**}$. It is also easily seen that the derivative is bounded away from 0 as long as $|w - W_{**}|$ is bounded away from both 0 and $+\infty$, which implies the convergence to W_{**}. ■

Now we address the choice of MID parameters u and d. Note that (7) is conveniently rewritten as

$$s = \frac{\log(1+u)}{\log(1+u) - \log(1-d)} \ . \qquad (9)$$

Hence, under the fixed-point approximation (and assuming the generic case $\max_i p_i < 1$), the conditional success probability s is completely determined by parameters u and d, which we can control. We choose u and d so that the value of s in (9) is equal to $s_* = 1/(e-1)$. This choice is motivated by the following simple facts. (The statement - and the proof - of Proposition 2(ii) are not quite formal, but it can easily be made a precise asymptotic statement.)

Proposition 2: (i) Suppose all p_i must be equal, i.e., all $\phi_i = a > 0$. Then, the vector p maximizing throughput $\mu(p)$ is $p^* = (1/M, \dots, 1/M)$, i.e., it is the vector satisfying $\sum_i p_i = 1$.
(ii) Suppose M is large and all numbers $p_i^* = \phi_i/[\sum_j \phi_j]$ are small. Then, the vector p maximizing $\mu(p)$ is approximately $p^* = (p_1^*, \dots, p_M^*)$ (i.e., the vector satisfying $\sum_i p_i = 1$), and the corresponding $s(p^*)$ is approximately $s_* = 1/(e-1)$.

Proof: (i) This follows from Theorem 1 in [19]. It is also easy to see directly, since in our case, $\mu(xp^*) = x(1 - x/M)^{M-1}$, and it is maximized over $x \geq 0$ by $x = 1$.
(ii) For $x \geq 0$, we have

$$\begin{aligned} \mu(xp^*) &= \sum_i xp_i^* \prod_{j\neq i}(1 - xp_j^*) \\ &\approx \sum_i xp_i^* e^{-x\sum_j p_j^*} \\ &= xe^{-x}. \end{aligned}$$

(The approximation above is "good" because each p_j^* is small.) The last expression is maximized by $x = 1$. ■

Remark 4: We will later discuss in Section VI some results of simulation to show that the throughput performance of the MID mechanism is in fact sensitive to the setting of parameters u and d, and the setting suggested by our analysis above indeed provides significantly better system throughput.

V. ANALYSIS OF 802.11 DCF BACKOFF WINDOW EVOLUTION

We next carry out a fixed-point approximation analysis of the backoff window W evolution under IEEE 802.11 DCF. We consider a simplified model where the minimum backoff window size $W_{min} = 1$ and there is no upper limit on W. When user window is set (or reset) to W, the user makes the next access attempt in a slot chosen randomly and uniformly between values 0 and $W - 1$. (In particular, this means that if $W = 1$, the user attempt an access immediately, in the next available slot.) If the access attempt is a success, the user window W is reset to $W_{min} = 1$; if it fails due to collision, the window is incremented by a fixed factor $(1 + u)$, with $u > 0$. We allow $1 + u$ to be not necessarily integer, and will ignore the effects of W rounding. Assume that users always have packets to transmit. The goal here is to find an approximation to the optimal value of u, which maximizes the overall channel throughput.

Assume further that the number of users M is large. Then in stationary regime, it will appear to any given user, say user i, that each other user $j \neq i$ accesses the channel in a given slot with some small probability $p_j = x > 0$, which is the same for all users, including user i itself. Thus, when user i accesses channel, the probability of a success (no collision) is approximately constant and equal to

$$\rho = \rho(x) = (1-x)^{M-1} \ . \qquad (10)$$

But, given this latter approximation, the dynamics of user i window is described by a simple regenerative process. The mean regeneration cycle duration T and the mean number of access attempts K within one cycle can be expressed in terms of ρ and u (as done in the sequel), and thus the equation

$$x \ = \ \frac{K}{T} \qquad (11)$$

defines x (and therefore the throughput $\mu = Mx(1-x)^{M-1}$) as a function of parameter u. The expressions for K and T are as follows:

$$\begin{aligned} K &= \rho \cdot 1 + (1-\rho)\rho \cdot 2 + (1-\rho)^2\rho \cdot 3 + \dots \\ &= \frac{1}{\rho} \end{aligned}$$

and

$$\begin{aligned} T &= \rho \cdot 1 + (1-\rho)\rho\frac{1}{2}[1 + (1+u)] \\ &\quad + (1-\rho)^2\rho\frac{1}{2}[1 + (1+u)^2] + \dots \ , \end{aligned}$$

which can be simplified to

$$T \ = \ \frac{1}{2\rho} + \frac{1}{2}\frac{1}{1 - (1-\rho)(1+u)} \ . \qquad (12)$$

To find the optimal value of u, we first observe that, since M is large, the second term in the RHS of (12) is necessarily very large, which means that, approximately, $(1-\rho)(1+u) = 1$. But, the optimal u must be such that, approximately, all $p_i =$

$x = 1/M$ (cf. Proposition 2), which implies $\rho \approx e^{-1}$. Thus the optimal value of u is close to

$$u_* = \frac{1}{1 - 1/e} - 1 = \frac{1}{e - 1} \ .$$

Hence, we have the following property (stated informally).

Proposition 3: For the 802.11 DCF backoff window update mechanism, as the number of contending users becomes large, the optimal value of the multiplicative increase factor $1 + u$ converges to $1 + u_* = \frac{e}{e-1} \approx 1.582$.

VI. PERFORMANCE COMPARISON

In this section, we carry out performance comparison of our proposed class of scheduling schemes, RCMAC, with that of the slotted Aloha and IEEE 802.11 DCF. As discussed earlier, we consider two versions of RCMAC: WP and TBR. For both of them, the dynamic weight of a user is set to be its packet queue length (unless specified otherwise) and the contention-level adaptation parameters are chosen as follows: $u = 0.2$ and $d = (1 - (1 + u)^{2-e}) \approx 0.123$ (cf. Section IV).

We first discuss the case of two users. We consider two types of traffic arrival processes: CBR and On/Off. In the former, each user has arrivals at constant bit rate; while in the latter, arrivals at each user are bursty, generated using standard two-state Markov model, with transition probabilities $p_{01} = 0.01$ and $p_{10} = 0.09$. Input arrival rates of the two users are chosen along the time-sharing line, so that the system is always saturated. We record the resulting user service rates, here averaged over 50000 slots, which provide a measure of system performance. (As we discuss later, for RCMAC-TBR, such saturation service rates do not necessarily lie on the boundary of its stability region. However, it is reasonable to expect that they provide a good approximation of this boundary.) Fig. 7 and Fig. 8 plot the user service rates obtained under various schemes for CBR and On/Off traffic, respectively.

IEEE 802.11 DCF performance shows significant throughput loss (w.r.t. slotted Aloha) for both CBR and On/Off traffic, which is due to large W_{min} (set as per standard to 32), leading to many idle slots. The performance will improve by lowering W_{min}. However, as mentioned earlier and discussed in [8], the optimal value of W_{min} varies with the number of users, and the current value is chosen in the standard to ensure both stable performance and user fairness for a sizable range of the number of users.

RCMAC performance, on the other hand, is only marginally inferior near symmetric rates, while better near extremes for TBR, as compared to the slotted Aloha for CBR arrivals (which is atypical of Internet traffic and a worst-case scenario for RCMAC). The marginal loss in throughput near symmetric rates is due to the relatively large value of W-adaptation parameters u and d, and the loss will diminish as they are made small. The current values of these parameters allow to achieve a compromise between the throughput loss and the system's ability to adapt to variation in user's dynamic weights and also, in general, to the number of active users in the system. We further note that RCMAC achieves those rates without requiring any a priori knowledge of the arrival rates, in contrast to the slotted Aloha, which can only achieve its stability region by setting user access probabilities optimally. Even more interestingly, when arrivals are bursty, which is more typical of Internet traffic, RCMAC-TBR in fact achieves significant improvement in user throughput as compared to the slotted Aloha, coming closer to the optimal time-sharing region.

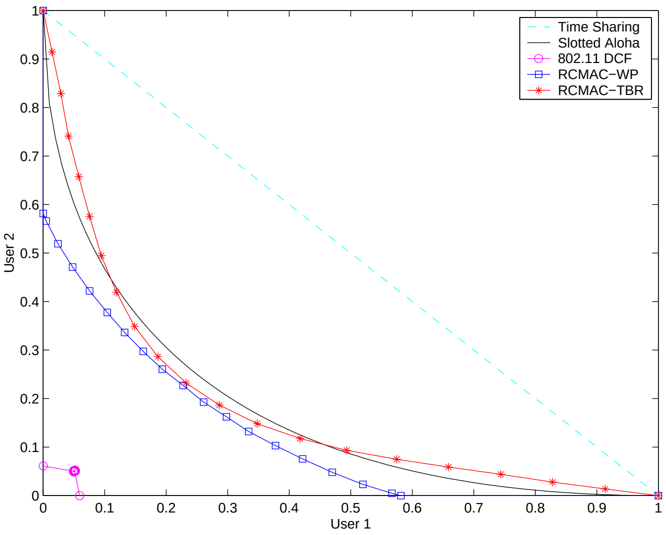

Fig. 7. Performance comparison for two-user scenario with CBR traffic.

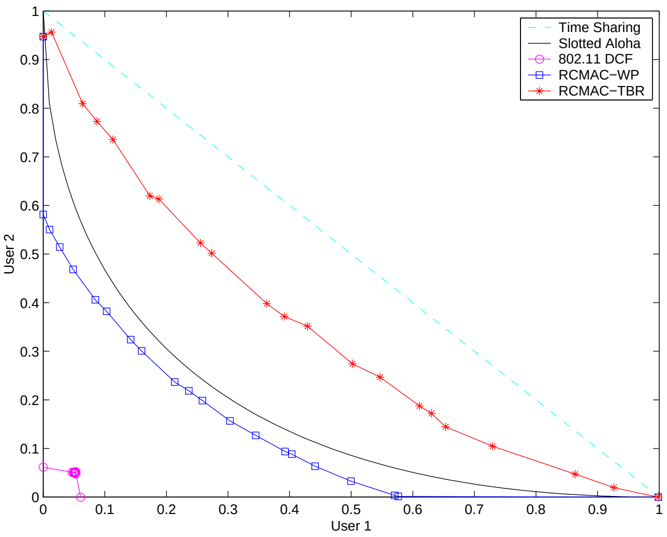

Fig. 8. Performance comparison for two-user scenario with On/Off traffic.

We next study the dependence of the total throughput on the number of users under various schemes. As before, we consider two types of traffic arrivals, CBR and On/Off, with symmetric arrival rates for users (other parameter settings are as above). Corresponding plots are given in Figs. 9 and 10, respectively. Again, IEEE 802.11 suffers from severe throughput degradation, which though reduces with the number of users (due to the large value of W_{min}). RCMAC-TBR, on the other hand, has only marginal loss in user throughput as compared to slotted Aloha for CBR, and obtains significant gains for the more typical On/Off traffic.

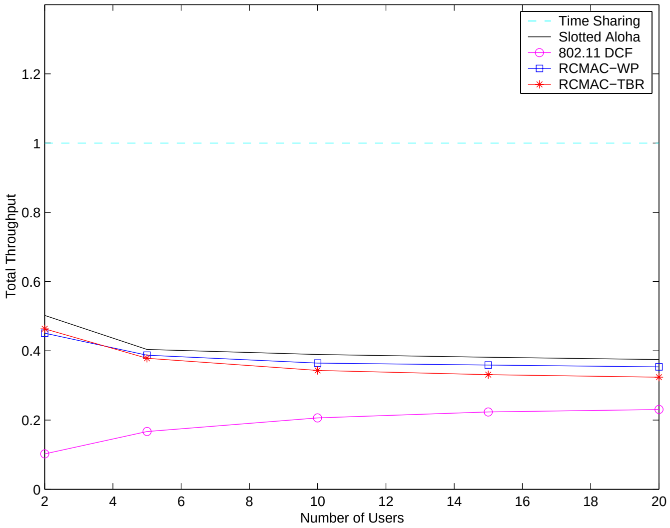

Fig. 9. Total throughput vs. number of nodes for CBR traffic.

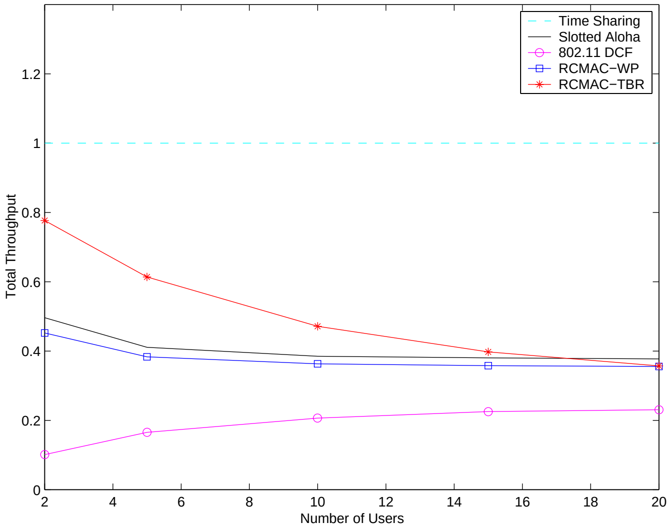

Fig. 10. Total throughput vs. number of nodes for On/Off traffic.

Next, we study the importance of judicious choice of the MID contention-level adaptation parameters u and d. Let us consider RCMAC-TBR with CBR arrivals. Fig. 11 plots the variation in the total throughput with the number of users for a number of u and d values (other parameter settings are as above). As the plot confirms, the parameter settings suggested by the analysis in Section IV indeed provide better system throughput for not just in the case of a large number of users (when it is naturally expected) but also when there are only few users.

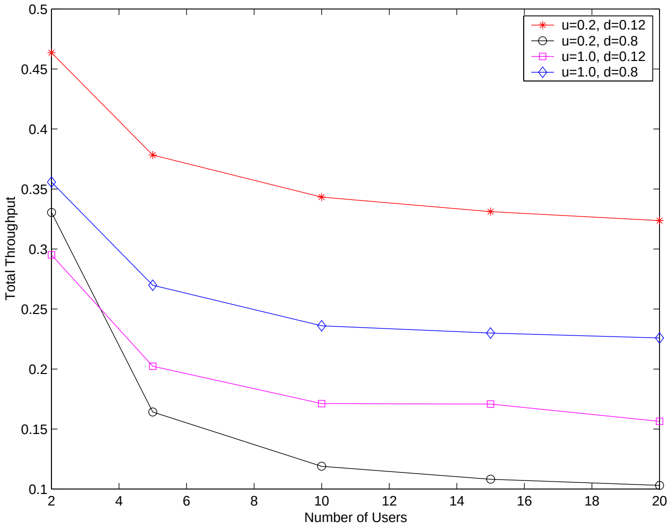

Fig. 11. Impact of the choices of MID parameters u and d on the system throughput.

Lastly, we discuss the performance of RCMAC in providing service differentiation. Suppose we would like to implement user throughput sharing which is akin to that provided by the generalized processor sharing (GPS) discipline [21], with some fixed user weights $\omega_i > 0$. (Without loss of generality we assume $\omega_i \geq 1$.) That is, if $R_i(t_1, t_2)$ is the amount of service received by user i during an interval $[t_1, t_2)$, then "ideally" we would like the following inequality to hold

$$\frac{R_i(t_1, t_2)}{R_j(t_1, t_2)} \geq \frac{\omega_i}{\omega_j}$$

for any user i that is continuously backlogged during the interval $[t_1, t_2)$. This would guarantee that a backlogged user i would get to transmit in at least $\omega_i / \sum_j \omega_j$ fraction of slots. To achieve this goal in our distributed framework, we employ RCMAC where each user i chooses its dynamic weight, q_i, to be its *effective rate deficiency*, γ_i, defined by

$$\gamma_i = 1 - \frac{\bar{R}_i}{\omega_i},$$

where $\bar{R}_i$ is the average rate of service received by user i. To estimate γ_i in an environment where the number of users in the system and their arrival rates may be time varying, a user employs the following exponential-forgetting adaptive rule:

$$\gamma_i(t) = (1-\alpha)\gamma_i(t-1) + \alpha \left(1 - \frac{I\{i \text{ served in slot } t\}}{\omega_i} \right),$$

where $\alpha > 0$ is the update step-size. In some scenarios, it may be desirable that users do not build service "credit" for slots in which they do not have packets to send. For this, the following modified rule may be used

$$\begin{aligned} \gamma_i(t) \;&=\; (1-\alpha)\gamma_i(t-1) + \alpha \Bigg(I\{i \text{ has non-empty} \\ &\qquad \text{queue}\} - \frac{I\{i \text{ served in slot } t\}}{\omega_i} \Bigg). \end{aligned} \tag{13}$$

With the above choice of user's dynamic weight, the service differentiation achieved by RCMAC-TBR, as well as its and the slotted Aloha total throughput, are plotted in Figure 12 for the two-user case. As the plot indicates, RCMAC-TBR is not only able to provide the desired differentiation between users but it also achieves higher total throughput than the pre-optimized slotted Aloha, where the user access probabilities were optimally chosen to achieve the desired differentiation.

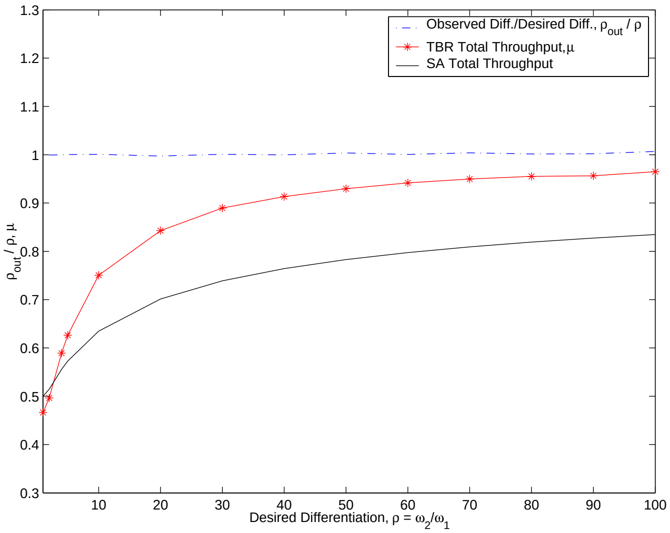

Fig. 12. Service differentiation and total throughput.

VII. Conclusions and Future Work

In this paper, we have proposed a class of distributed scheduling schemes, Regulated Contention Multiple Access Control (RCMAC). Unlike the slotted Aloha or IEEE 802.11, or even more recent IEEE 802.11e, RCMAC can provide dynamic service differentiation between users in a quantifiable manner. By regulating multi-user contention, RCMAC is also able to achieve higher throughput when traffic is bursty, as is typically the case. To achieve these, RCMAC introduces only two additional parameters, contention level and access threshold, to be included within the existing RTS/CTS signaling mechanism.

The principles of threshold-based contention regulation are generic and can be applied to a wide range of other distributed networks. For instance, in dense networks of sensors [2], multiple nodes in proximity observe a single event. They then compete for channel access, thus resulting in collisions and wasting scarce energy resources. However, in order to detect event features reliably at the sink, a subset of transmissions may suffice. In such scenarios, by suitable choice of the dynamic thresholding function $\tau(t)$, reliable communication may be achieved with minimum energy expenditure. For instance, $\tau(t)$ can be a function of the energy remaining at a sensor node and the current reliability level.

A number of important issues need further exploration:

- The stability region of RCMAC-TBR, i.e, the set of arrival vectors that RCMAC-TBR can sustain, needs to be analyzed. Unlike RCMAC-WP or 802.11 DCF, the boundary rates are not determined by simply saturating the system. Due to threshold-limited contention, one needs to track the process associated with the difference of queue lengths rather than the queue lengths themselves.
- Our discussion in this paper has focused on the single-hop scenario, where a number of transmitters compete for access to the shared channel. Some scenarios, such as in ad hoc networks and sensor networks, may involve multi-hop wireless networking (cf. Fig. 13). A sufficiently robust distributed scheduling approach for the single-hop case should also perform well in multi-hop networks. Nonetheless, the contention neighborhood in the latter case is much broader and includes neighbors of immediate neighbors. Extending RCMAC for multi-hop scenario is a part of future work. It would be interesting to see if it can achieve enough spatial reuse to have the same scaling in the system's throughput with the number of nodes in the network as obtained in [14].

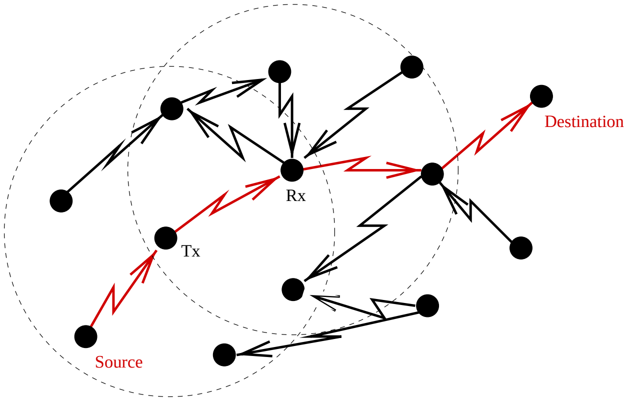

Fig. 13. Multi-hop wireless network.

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