

# Utility-Optimal Random Access for Wireless Multimedia Networks

Man Hon Cheung, Hamed Mohsenian-Rad, *Member, IEEE*,  
Vincent W.S. Wong, *Senior Member, IEEE*, and Robert Schober, *Fellow, IEEE*

**Abstract**—In this letter, we consider the uplink random access problem in a wireless multimedia network (WMN) with audio, video, and best effort applications. Since these multimedia applications have different quality-of-service (QoS) requirements, we model their utilities with concave, step, and quasi-concave functions. We assume that the access point performs admission control and assigns transmission probabilities to the users for random access, based on solving a non-convex network utility maximization problem. We propose a novel enumeration algorithm to obtain the *global optimal* solution by solving a number of computationally tractable convex optimization problems. We characterize the total number of iterations of the algorithm analytically. Simulation results show that our proposed algorithm achieves a higher average network aggregate utility than a carrier sense multiple access (CSMA) scheme implemented in a slotted time system.

**Index Terms**—Random access, wireless multimedia networks.

## I. INTRODUCTION

IN a wireless multimedia network (WMN), the multimedia applications are commonly supported by two main types of medium access control (MAC) protocols, contention-free *scheduling* protocols and contention-based *random access* protocols. Due to their flexibility and efficiency in resource sharing for bursty multimedia traffic [1], random access protocols have received significant attention for improving the performance of wireless multimedia communications [1]–[4].

In this letter, we propose a utility-optimal algorithm for uplink random access in WMNs. Different from the previously proposed heuristic MACs for WMNs (e.g., [1]–[4]), we design the algorithm *analytically* based on the mathematical framework of network utility maximization (NUM). Previous works on random access, such as [5], [6], have focused on solving the NUM problem to achieve efficiency and fairness for non-real-time applications (e.g., file transfer and electronic mail) with *elastic traffic* only, where the utility functions of the applications are *concave*. Here, we also include the more challenging case of *inelastic traffic* in real-time multimedia applications (e.g., video streaming), which have *inelastic* demand for bandwidth [7]. Different from [8] that considered sigmoidal utility functions for inelastic traffic, we model the utilities of applications with inelastic traffic using *step* or *quasi-concave* utility functions. As a result, the formulated NUM problem in this letter is *non-convex* and is difficult to solve in general. We

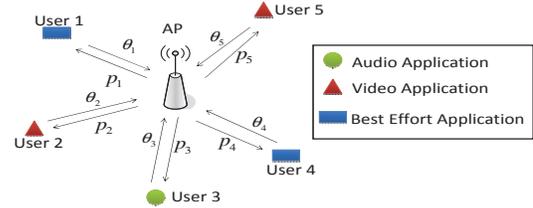


Fig. 1. A WMN with a set of users  $\mathcal{N} = \{1, 2, 3, 4, 5\}$ . In our system model, user  $i$  first declares the AC of its application  $\theta_i$  to the AP. After receiving  $\theta_i, \forall i \in \mathcal{N}$ , the AP assigns the transmission probabilities  $\mathbf{p} = (p_1, p_2, p_3, p_4, p_5)$  to the users for random access based on NUM.

propose an enumeration algorithm to obtain the *global optimal* solution for the formulated non-convex problem by solving a number of *convex* optimization problems. To the best of our knowledge, this work is the first study on NUM for random access with both elastic and inelastic traffic using concave, step, and quasi-concave utility functions related to multimedia applications in WMNs.

## II. SYSTEM MODEL

As shown in Fig. 1, we consider a WMN with one access point (AP) and  $N$  users. The users run audio, video, and best effort applications with different quality-of-service (QoS) requirements. We assume that the users are one-hop neighbors to the AP, and we denote the set of users by  $\mathcal{N} = \{1, 2, \dots, N\}$ . We consider the uplink random access scenario, where the users transmit multimedia content to the AP based on a simple slotted-Aloha MAC. Specifically, we consider the centralized setting, where user  $i \in \mathcal{N}$  first declares its access category (AC)  $\theta_i$  to the AP. In return, the AP assigns *transmission probability*  $p_i$  to user  $i \in \mathcal{N}$ . User  $i \in \mathcal{N}$  then attempts to access the shared wireless channel at the beginning of each time slot with probability  $p_i$ . At a given time slot, let  $p_i^{\text{succ}}$  be the probability that a transmission from user  $i \in \mathcal{N}$  is successful, i.e., a collision does not occur. For the case with *saturated* traffic, we have

$$p_i^{\text{succ}}(\mathbf{p}) = p_i \prod_{j \in \mathcal{N} \setminus \{i\}} (1 - p_j), \quad \forall i \in \mathcal{N}, \quad (1)$$

where vector  $\mathbf{p} = (p_i, i \in \mathcal{N})$ . Given the *nominal* data rate  $\varphi$ , the *average* data rate for user  $i$  is obtained as  $\varphi p_i^{\text{succ}}(\mathbf{p})$ . We define the delay as the duration (in terms of the number of time slots) from the moment the packet reaches the head-of-line in a queue to the moment that it is successfully received by the AP. In this way, the delay of user  $i \in \mathcal{N}$  is a geometric random variable with parameter  $p_i^{\text{succ}}(\mathbf{p})$ . Thus, the *average delay* for user  $i$ 's packets is given by  $1/p_i^{\text{succ}}(\mathbf{p}) - 1$ .

For each user  $i \in \mathcal{N}$ , we use a nondecreasing utility function  $U_i(p_i^{\text{succ}}(\mathbf{p}))$  to model the level of satisfaction that

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it experiences when it attains success probability  $p_i^{\text{succ}}(\mathbf{p})$ . Let  $\mathcal{N}_{\mathcal{E}}$  be the set of best effort applications with elastic traffic, and  $\mathcal{N}_{\mathcal{I}}$  be the set of audio and video applications with inelastic traffic. We refer to the users in  $\mathcal{N}_{\mathcal{E}}$  and  $\mathcal{N}_{\mathcal{I}}$  as elastic and inelastic users, respectively. Note that  $\mathcal{N}_{\mathcal{E}} \cap \mathcal{N}_{\mathcal{I}} = \emptyset$  and  $\mathcal{N}_{\mathcal{E}} \cup \mathcal{N}_{\mathcal{I}} = \mathcal{N}$ . We let  $\mathcal{M} \subseteq \mathcal{N}_{\mathcal{I}}$  be the set of those inelastic users who are admitted to the system. For each best effort application  $j \in \mathcal{N}_{\mathcal{E}}$ , we can use a *concave* function to model its utility. A common class of concave utility functions is the  $\alpha$ -fair utility function [9]:

$$U_i(p_i^{\text{succ}}(\mathbf{p}), \alpha_i, K_i, L_i) = \begin{cases} K_i \left( \ln(p_i^{\text{succ}}(\mathbf{p})) + L_i \right), & \text{if } \alpha_i = 1, \\ K_i \left( \frac{p_i^{\text{succ}}(\mathbf{p})^{1-\alpha_i}}{1-\alpha_i} + L_i \right), & \text{if } \alpha_i > 1, \end{cases} \quad (2)$$

where  $U_i$  is user  $i$ 's obtained utility value,  $\alpha_i \geq 1$  is a fixed utility parameter,  $K_i \geq 0$  is an amplitude parameter, and  $L_i$  is a parameter that adjusts the vertical position of the curve.

On the other hand, each audio or video application  $i \in \mathcal{N}_{\mathcal{I}}$  may have tight QoS requirements and require some minimum level of available bandwidth. If the available bandwidth drops below the required threshold, then the connection will become useless, leading to zero utility for the corresponding user. Therefore, we propose to use two types of utility functions to model inelastic traffic: *step* functions and *quasi-concave* functions. A step utility function is characterized by parameters  $K_i$  and  $p_i^{\text{critical}}$ . Parameter  $p_i^{\text{critical}} \geq 0$  refers to the *minimum* required  $p_i^{\text{succ}}(\mathbf{p})$  for the application to run properly in user  $i \in \mathcal{N}_{\mathcal{I}}$ . Parameter  $K_i$  determines the amplitude of the utility function if the required  $p_i^{\text{critical}}$  is achieved. Step utility functions are used to mathematically model various *hard real-time* audio/video applications, which cannot operate if the minimum required data rate is not provided [7]. That is,

$$U_i(p_i^{\text{succ}}(\mathbf{p}), K_i, p_i^{\text{critical}}) = \begin{cases} K_i, & \text{if } p_i^{\text{succ}}(\mathbf{p}) \geq p_i^{\text{critical}}, \\ 0, & \text{if } p_i^{\text{succ}}(\mathbf{p}) < p_i^{\text{critical}}. \end{cases} \quad (3)$$

Furthermore, for *rate-adaptive* audio/video applications with minimum bandwidth requirements, the utility functions are usually quasi-concave [10, pp. 95]. We introduce a new quasi-concave utility function, which we refer to as  $\alpha$ -critical utility function, by modifying the  $\alpha$ -fair utility function in (2). If  $\alpha_i = 1$ , we have

$$U_i(p_i^{\text{succ}}(\mathbf{p}), \alpha_i, K_i, p_i^{\text{critical}}) = \begin{cases} K_i \ln\left(\frac{p_i^{\text{succ}}(\mathbf{p})}{p_i^{\text{critical}}}\right), & \text{if } p_i^{\text{succ}}(\mathbf{p}) \geq p_i^{\text{critical}}, \\ 0, & \text{if } p_i^{\text{succ}}(\mathbf{p}) < p_i^{\text{critical}}. \end{cases} \quad (4)$$

If  $\alpha_i > 1$ , then the  $\alpha$ -critical utility function is given by

$$U_i(p_i^{\text{succ}}(\mathbf{p}), \alpha_i, K_i, p_i^{\text{critical}}) = \begin{cases} \frac{K_i}{1-\alpha_i} \left[ (p_i^{\text{succ}}(\mathbf{p}))^{1-\alpha_i} - (p_i^{\text{critical}})^{1-\alpha_i} \right], & \text{if } p_i^{\text{succ}}(\mathbf{p}) \geq p_i^{\text{critical}}, \\ 0, & \text{if } p_i^{\text{succ}}(\mathbf{p}) < p_i^{\text{critical}}. \end{cases} \quad (5)$$

Clearly, both  $\alpha$ -critical and step utility functions are *non-concave* and *non-differentiable*. Examples for the utility functions that we consider in this letter are shown in Fig. 2.

Next, we define the AC of user  $i \in \mathcal{N}$  as the utility parameters that characterize its utility function. That is, if

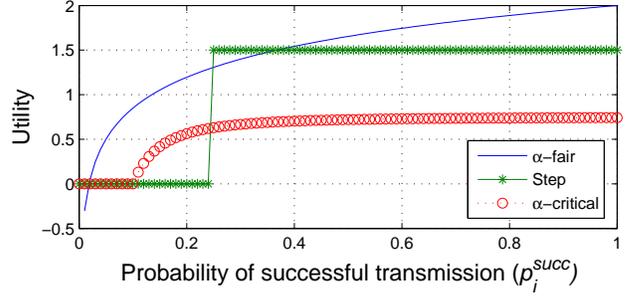


Fig. 2. Three different types of utility functions considered in this letter: (1) Concave function:  $\alpha$ -fair function ( $K_i = 0.5$ ,  $\alpha_i = 1$ , and  $L_i = 4$ ), (2) Step function ( $K_i = 1.5$  and  $p_i^{\text{critical}} = 0.25$ ), and (3) Quasi-concave function:  $\alpha$ -critical function ( $K_i = 0.015$ ,  $\alpha_i = 3$ , and  $p_i^{\text{critical}} = 0.1$ ).

utility function  $U_i$  is a concave  $\alpha$ -fair function as in (2), then  $\theta_i = \{K_i, \alpha_i, L_i\}$ . If utility function  $U_i$  is a step function as in (3), then  $\theta_i = \{K_i, p_i^{\text{critical}}\}$ . Finally, if it is an  $\alpha$ -critical function as in (4) and (5), then  $\theta_i = \{K_i, \alpha_i, p_i^{\text{critical}}\}$ .

We assume that the AP assigns transmission probabilities and performs *admission control* by solving the following *weighted NUM* problem [5], [6], [11]:

$$\underset{\mathbf{p} \in \mathcal{P}}{\text{maximize}} \quad \sum_{j \in \mathcal{N}_{\mathcal{E}}} w_j U_j(p_j^{\text{succ}}(\mathbf{p}), \theta_j) + \sum_{i \in \mathcal{N}_{\mathcal{I}}} w_i U_i(p_i^{\text{succ}}(\mathbf{p}), \theta_i), \quad (6)$$

where  $\mathcal{P} = \{\mathbf{p} : 0 \leq p_i \leq 1, \forall i \in \mathcal{N}\}$  represents the set of all feasible transmission probabilities. The *priority weight*  $w_i$  is controlled by the AP for flexible admission control and protection of existing services [2]. Notice that problem (6) is a *non-convex* and *non-differentiable* optimization problem due to the product form in (1) and the use of non-concave and non-differentiable step and  $\alpha$ -critical utility functions. For the rest of the letter, we let  $u_i(p_i^{\text{succ}}(\mathbf{p}), \theta_i) = w_i U_i(p_i^{\text{succ}}(\mathbf{p}), \theta_i)$  for all  $i \in \mathcal{N}$ .

### III. UTILITY-OPTIMAL RANDOM ACCESS FOR WMNS

In this section, we propose a utility-optimal random access algorithm for WMNs to obtain the global optimal solution of problem (6) by iteratively solving a number of convex optimization problems. Although we only consider  $\alpha$ -fair functions for concave functions and  $\alpha$ -critical functions for quasi-concave functions in this letter, our approach can be applied to any similar continuous nondecreasing function.

*Lemma 1:* At any optimal solution of problem (6), denoted by  $\mathbf{p}^*$ , for all inelastic users  $i \in \mathcal{N}_{\mathcal{I}}$ , we have either  $p_i^{\text{succ}}(\mathbf{p}^*) \geq p_i^{\text{critical}}$  or  $p_i^{\text{succ}}(\mathbf{p}^*) = 0$ .

*Proof:* We prove this lemma by contradiction. Assume that at optimality, we have  $0 < p_i^{\text{succ}}(\mathbf{p}^*) < p_i^{\text{critical}}$  for some user  $i \in \mathcal{N}_{\mathcal{I}}$ . Since the minimum required success probability is not satisfied for user  $i \in \mathcal{N}_{\mathcal{I}}$ , we have  $u_i = 0$ . Thus, the objective function of problem (6) at optimality becomes

$$\sum_{j \in \mathcal{N}_{\mathcal{E}}} u_j(p_j^{\text{succ}}(\mathbf{p}^*), \theta_j) + \sum_{k \in \mathcal{N}_{\mathcal{I}} \setminus \{i\}} u_k(p_k^{\text{succ}}(\mathbf{p}^*), \theta_k). \quad (7)$$

On the other hand, from (1), the success probability  $p_j^{\text{succ}}(\mathbf{p})$  is a decreasing function of  $p_i$  for any  $j \neq i$ . Therefore, the summation in (7) is decreasing in  $p_i^*$  and at optimality we have

$p_i^* = 0$ . This implies that  $p_i^{\text{succ}}(\mathbf{p}^*) = 0$  which contradicts our assumption that  $0 < p_i^{\text{succ}}(\mathbf{p}^*) < p_i^{\text{critical}}$ . ■

From Lemma 1, the AP either does not admit an inelastic user  $i \in \mathcal{N}_{\mathcal{I}}$ , or if it admits a user  $i \in \mathcal{N}_{\mathcal{I}}$ , then it guarantees to provide it with its minimum required success probability  $p_i^{\text{critical}}$ . Thus, we can obtain the optimal value of problem (6) by considering all subsets of users  $\mathcal{M} \subseteq \mathcal{N}_{\mathcal{I}}$  admitted:

$$\underset{\mathcal{M} \subseteq \mathcal{N}_{\mathcal{I}}}{\text{maximize}} \quad v(\mathcal{M}), \quad (8)$$

where

$$\begin{aligned} v(\mathcal{M}) \triangleq & \underset{\mathbf{x}, \mathbf{p} \in \mathcal{P}}{\text{maximum}} \quad \sum_{j \in \mathcal{N}_{\mathcal{E}}} u_j(x_j, \theta_j) + \sum_{i \in \mathcal{N}_{\mathcal{I}}} u_i(x_i, \theta_i) \quad (9) \\ \text{subject to} \quad & 0 \leq x_i \leq p_i^{\text{succ}}(\mathbf{p}), \quad \forall i \in \mathcal{N}_{\mathcal{E}} \cup \mathcal{M}, \\ & p_i^{\text{critical}} \leq p_i^{\text{succ}}(\mathbf{p}), \quad \forall i \in \mathcal{M}, \\ & p_i = 0, \quad \forall i \in \mathcal{N}_{\mathcal{I}} \setminus \mathcal{M}. \end{aligned}$$

In problem (9), the auxiliary variable  $x_i$  in the first constraint represents the probability of successful transmission for user  $i$ 's packets [5]. We divide the set of inelastic users  $\mathcal{N}_{\mathcal{I}}$  into two subsets: subset  $\mathcal{M}$  and subset  $\mathcal{N}_{\mathcal{I}} \setminus \mathcal{M}$ , where  $\mathcal{M}$  acts as an auxiliary set to model *admission control*. Note that problem (9) involves both elastic and inelastic users. For each inelastic user  $i \in \mathcal{M}$ , problem (9) includes the extra constraint  $p_i^{\text{succ}}(\mathbf{p}) \geq p_i^{\text{critical}}$  such that all admitted inelastic users achieve their minimum required success probabilities  $p_i^{\text{critical}}$ . On the other hand, for each inelastic user  $i \in \mathcal{N}_{\mathcal{I}} \setminus \mathcal{M}$ , which is not admitted, we include the constraint  $p_i = 0$  to make sure that no transmission probability is allocated to it. By taking the logarithm of both sides of the first and second constraints in (9) and a logarithmic change of variables  $x'_i = \ln x_i$  and  $u'_i(x'_i, \theta_i) = u_i(e^{x'_i}, \theta_i)$ , we can reformulate problem (9) as

$$\begin{aligned} \underset{\mathbf{x}', \mathbf{p} \in \mathcal{P}}{\text{maximum}} \quad & \sum_{j \in \mathcal{N}_{\mathcal{E}}} u'_j(x'_j, \theta_j) + \sum_{i \in \mathcal{N}_{\mathcal{I}}} u'_i(x'_i, \theta_i) \quad (10) \\ \text{subject to} \quad & x'_i \leq \ln p_i + \sum_{j \in \mathcal{N} \setminus \{i\}} \ln(1-p_j), \quad \forall i \in \mathcal{N}_{\mathcal{E}} \cup \mathcal{M}, \\ & \ln p_i^{\text{critical}} \leq \ln p_i + \sum_{j \in \mathcal{N} \setminus \{i\}} \ln(1-p_j), \quad \forall i \in \mathcal{M}, \\ & p_i = 0, \quad \forall i \in \mathcal{N}_{\mathcal{I}} \setminus \mathcal{M}, \end{aligned}$$

where the optimal value of problem (10) remains  $v(\mathcal{M})$ . Following a similar analysis as in [5], we can show that problem (10) is *convex*. Therefore, it can be solved using the *interior point method* [10].

In a WMN, since the number of ACs available is limited in practice, there are many *redundant* iterations in problem (8) that can be eliminated. That is, some values of  $v(\mathcal{M})$  can be obtained from the results in previous iterations. When  $\mathcal{M} \subseteq \mathcal{N}_{\mathcal{I}}$  is given, let  $\mathcal{M}(\theta) = (i \in \mathcal{M} : \theta_i = \theta)$  be the inelastic users in set  $\mathcal{M}$  with declared AC equal to  $\theta$ . We define the *equivalent AC sets* as follows:

*Definition 1:* A pair of sets  $\mathcal{M}_1, \mathcal{M}_2 \subseteq \mathcal{N}_{\mathcal{I}}$  are equivalent AC sets if  $|\mathcal{M}_1(\theta)| = |\mathcal{M}_2(\theta)|, \forall \theta \in \Theta$ , where  $\Theta$  is the set of all ACs for inelastic users. In other words, sets  $\mathcal{M}_1$  and  $\mathcal{M}_2$  have the same number of users in each AC.

As an example, for  $\mathcal{M}_1 = \{2, 3, 4\}$  and  $\mathcal{M}_2 = \{2, 3, 5\}$ , if inelastic users 4 and 5 belong to the same AC, then  $\mathcal{M}_1$  and  $\mathcal{M}_2$  are equivalent AC sets.

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**Algorithm 1** *Utility-optimal random access algorithm for WMNs with  $\alpha$ -fair, step, and  $\alpha$ -critical utility functions.*

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1: Input:  $\theta_i, \forall i \in \mathcal{N}$ 
2: (Initialization) Set  $s := -\infty, \mathbf{p}^* := \mathbf{0}, \mathcal{M}^* := \emptyset$ , and  $\Psi := \emptyset$ 
3: for all subsets  $\mathcal{M}$  of  $\mathcal{N}_{\mathcal{I}}$  do
4:   if  $\mathcal{M}$  and  $\tilde{\mathcal{M}}$  are not equivalent AC sets,  $\forall \tilde{\mathcal{M}} \in \Psi$ ,
     as defined in Definition 1, then
5:     Set  $\Psi := \Psi \cup \mathcal{M}$ 
6:   end if
7: end for
8: for all  $\mathcal{M} \in \Psi$  do
9:   Solve problem (10) for  $v(\mathcal{M})$  and the optimal solution  $\mathbf{p}$  using
     the interior point method
10:  if  $v(\mathcal{M}) > s$ , then
11:    Set  $s := v(\mathcal{M}), \mathbf{p}^* := \mathbf{p}$ , and  $\mathcal{M}^* := \mathcal{M}$ 
12:  end if
13: end for
14: Output:  $\mathbf{p}^*$  and  $\mathcal{M}^*$ 

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*Lemma 2:* If  $\mathcal{M}_1, \mathcal{M}_2 \subseteq \mathcal{N}_{\mathcal{I}}$  are equivalent AC sets, then we necessarily have  $v(\mathcal{M}_1) = v(\mathcal{M}_2)$ .

*Proof:* Since  $\mathcal{M}_1$  and  $\mathcal{M}_2$  have the same number of users in every AC, the optimization problems defined in (9) for  $\mathcal{M}_1$  and  $\mathcal{M}_2$  have the same objective functions and constraints. Thus, we have  $v(\mathcal{M}_1) = v(\mathcal{M}_2)$ . ■

In problem (8), after solving problem (10) for  $v(\mathcal{M}_1)$ , we do not have to solve it again for  $v(\mathcal{M}_2)$  if  $\mathcal{M}_1$  and  $\mathcal{M}_2$  are equivalent AC sets due to Lemma 2. In this way, instead of considering problem (8), we just need to solve

$$\underset{\mathcal{M} \in \Psi}{\text{maximize}} \quad v(\mathcal{M}), \quad (11)$$

where  $\Psi$  is a subset of set  $\mathcal{N}_{\mathcal{I}}$ 's power set formed by keeping only one equivalent AC set when multiple equivalent AC sets are encountered.  $\Psi$  represents the set of different combinations of inelastic users that should be considered for admission.

We propose Algorithm 1 to find the global optimal solution of problem (6) by solving problem (11). From lines 3 to 7, we first record the non-equivalent AC sets in  $\Psi$ . In line 9, the allocated transmission probability  $\mathbf{p}$  for the given set  $\mathcal{M}$  is calculated. Set  $\mathcal{M}$  and the corresponding  $\mathbf{p}$  that result in the largest aggregate utility so far are recorded in lines 10 to 12. In line 14,  $\mathbf{p}^*$  is the resulting optimal solution of optimization problem (6) for random access and  $\mathcal{M}^*$  is the resulting set of inelastic users admitted for optimal admission control.

Next, we characterize the total number of iterations required for solving problem (11), which is equal to  $|\Psi|$ . Let  $I$  be the total number of different types of inelastic ACs in the system. We perform a one-to-one mapping between an inelastic AC and  $l = 1, \dots, I$ . Let  $N_{\mathcal{I}}^l$  be the total number of type  $l$  inelastic users. So  $\sum_{l=1}^I N_{\mathcal{I}}^l = |\mathcal{N}_{\mathcal{I}}|$ .

*Lemma 3:* The number of iterations required in solving problem (11) is  $|\Psi| = \prod_{l=1}^I (N_{\mathcal{I}}^l + 1)$ .

*Proof:* The formation of the set  $\Psi$  is equivalent to formation of combinations with identical objects from a set with  $N_{\mathcal{I}}^l$  type  $l$  objects,  $l = 1, \dots, I$ . Notice that in each combination, there can be zero to  $N_{\mathcal{I}}^l$  type  $l$  objects, so there are  $N_{\mathcal{I}}^l + 1$  possibilities regarding the type  $l$  object. Thus, the total number of combinations with  $I$  different types of identical objects is given by  $\prod_{l=1}^I (N_{\mathcal{I}}^l + 1)$ . ■

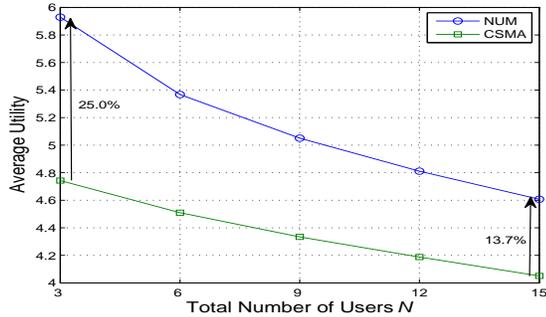


Fig. 3. Average utility in the system achieved by our NUM-based random access scheme and a CSMA scheme versus the total number of users  $N$  in the system.

#### IV. PERFORMANCE EVALUATION

In this section, we assess the performance of our proposed random access scheme using MATLAB. We first compare our random access scheme with a CSMA scheme implemented in a slotted time system. Its operation is similar to the one used in the IEEE 802.11e standard with different contention window sizes for different ACs. However, the interframe spacing of the IEEE 802.11e standard is not implemented in the CSMA scheme. Let  $aCW_{min}$  and  $aCW_{max}$  be the two parameters related to the contention window sizes. For the CSMA scheme, we assume that three ACs are available with different minimum and maximum contention window sizes [12, pp. 131]:  $aCW_{min}$  and  $aCW_{max}$  for AC 1 (best effort),  $(aCW_{min} + 1)/2 - 1$  and  $aCW_{min}$  for AC 2 (video), and  $(aCW_{min} + 1)/4 - 1$  and  $(aCW_{min} + 1)/2 - 1$  for AC 3 (voice). We assume that the number of users in each AC is the same such that there are  $N/3$  users in each AC. The utility functions of the users are as follows: a step function with parameters  $K_i = 10$  and  $p_i^{critical} = 0.03$  for each audio application, an  $\alpha$ -critical utility function with parameters  $K_i = 1.2$ ,  $\alpha_i = 1$ , and  $p_i^{critical} = 0.0012$  for each video application, and an  $\alpha$ -fair utility function with parameters  $K_i = 0.5$ ,  $\alpha_i = 1$ , and  $L_i = 4$  for each best effort application. Note that the utility of the step utility function is the highest and that of the  $\alpha$ -fair utility function is the lowest. From the nature and utilities of the applications, we map the audio applications to AC 3 (voice), the video applications to AC 2 (video), and the best effort applications to AC 1 (best effort). We choose  $aCW_{min} = 63$ ,  $aCW_{max} = 1023$  [12, pp. 589]. As shown in Fig. 3, the performance improvement of the average utility (i.e., the aggregate utility divided by  $N$ ) in the system of our scheme over the CSMA scheme is 25.0% for  $N = 3$  and 13.7% for  $N = 15$ .

Next, we compare the computational complexity of Algorithm 1 with an *exhaustive search*. Specifically, to solve problem (6), we compare the number of iterations that  $v(\mathcal{M})$  is evaluated in problem (11) (i.e., by Algorithm 1) and in problem (8) (i.e., by an exhaustive search). We assume that there are four ACs, where two ACs are for inelastic traffic and two ACs are for elastic traffic. Also, we assume that there are  $N/4$  users in each AC. As shown in Fig. 4, by eliminating a significant number of redundant computations due to the equivalent AC sets from Lemma 2, Algorithm 1 has a much lower computational complexity than an exhaustive

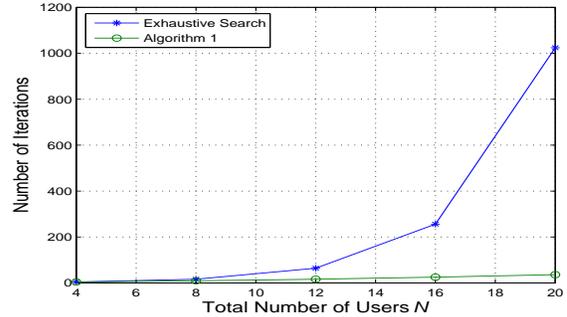


Fig. 4. Number of iterations required to obtain the optimal solution with Algorithm 1 and an exhaustive search. We can see that Algorithm 1 has a much lower computational complexity than an exhaustive search.

search. The simulation results also verify Lemma 3. Moreover, we note that the solutions obtained by Algorithm 1 and an exhaustive search are indeed the same.

#### V. CONCLUSION

In this letter, we studied the problem of assigning transmission probabilities to audio, video, and best effort applications for random access in WMNs. We obtained the global optimal solution of the formulated non-convex NUM problem by solving a number of convex optimization problems. We characterized the number of iterations required analytically. Simulation results show that our proposed scheme achieves a higher average utility than a slotted-time CSMA scheme. An interesting topic for future work is the extension of our model to a multi-hop setting for data transmission.

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