Distributed Rate and Admission Control in Home M2M networks: A Non-cooperative Game Approach

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***Abstract*—It is envisioned that home networks will shift from the current machine-to-human communications to the machine-to-machine (M2M) paradigm with the rapid penetration of embedded devices in home surroundings. In this paper, we first proposed an architecture of home M2M networks that is decomposed into three sub-areas depending on the radio service ranges and potential applications. We then concentrate on the Quality-of-Service (QoS) management in home M2M networks. Although generic QoS architectures for home M2M networks have been proposed in existing standards, the concrete QoS schemes and algorithms are still missing. Based on the proposed architecture, a cross-layer design of distributed admission and rate control is put forwarded. This proposed scheme, named DRAC, is integrated with a game theory analysis module to model the competition of radio bandwidth among M2M home devices, and embrace the distributed operations of QoS-aware and fair sharing in transmission opportunities. Simulation results indicate that the proposed DRAC scheme allows the M2M home devices to intelligently share the radio bandwidth based on QoS demands in resource-constrained home M2M networks.**

***Index Terms*—Home M2M communications, architecture, QoS improvement, multimedia sharing**

I. INTRODUCTION

Home networks are rapidly developing to include a large diversity of devices/machines/teminals, including mobile phones, personal computers, laptops, TVs, speakers, lights, and electronic appliances. With the dramatic penetration of embedded devices, Machine-to-Machine (M2M) communications will become a dominant communication paradigm in home networks which currently concentrate on machine-to-human or human-to-human information production, exchange, and processing. M2M communications is characterized by low-power, low-cost, and low human intervention [1], [2]. M2M communications is typically composed of a number of networked devices and a gateway. The gateway is responsible for the connection among the devices, and the connection between the M2M communications area and other networks, e.g., Internet. The M2M network may use an appropriate standardized radio technology based on the requirements of a specific application. From data management perspective, M2M communications consists of three phases: data collection, data transmission, and data processing. The data collection phase refers to the procedure on how to obtain the physical data. The data transmission phase shows the mechanisms on how to deliver the collected data from the communications area to an external server. The data processing phase is the process of dealing with and analyzing the data; and also provides feedback on how to control the application. Machines are normally small and inexpensive, which puts several constraints in M2M communications, including energy, computation, storage, and bandwidth. These constraints pose a number of unique challenges in the design of home M2M networks to achieve a highly connected, efficient, and reliable home. This paper is motivated to present a possible network architecture and a distributed rate and admission control scheme in home M2M networks.

The rest of the paper is organized as follows. Section II illustrates the home M2M network architecture. Section III explains the operation procedure and basic mechanism of the proposed Distributed Rate and Admission Control (DRAC) scheme. Section IV and V present the simplified delay analysis model and the game theory framework in DRAC, respectively. Section VI evaluates the performance of DRAC and Section VII concludes the paper.

II. DISTRIBUTED RATE AND ADMISSION CONTROL

Multimedia sharing is a predominant service in home M2M networks. Usually, multimedia sharing in home M2M networks contains three main steps: multimedia discovery, transmission, and rendering. Though the existing standards, such as DLNA and Intelligent Grouping and Resource Sharing (IGRS), have defined the generic QoS architectures for multimedia sharing, the specific QoS management algorithms are still missing. In this section, based on the proposed home M2M network architecture, we propose a distributed rate and admission control scheme to improve the QoS of multimedia sharing. The proposed scheme adopts a cross-layer design approach and integrates a game theory framework to model the contention of radio resource among multiple service flows.

A. Architecture of Home M2M Networks

The home M2M network is essentially a heterogeneous network that consists of a backbone network and multiple sub-networks. In the backbone network, there is a central machine *home central gateway (HGW)*, managing the whole network and connecting the home network to outside world, e.g., Internet. Each sub-network operates in a self-organization manner and may be designed for a specific application. Each sub-network has a *sub-gateway (SGW)* as an endingpoint to connect the sub-network to HGW as well as the backbone network. It is noteworthy that both HGW and SGW are logical entities and their functionalities can be physically implemented in a single device, i.e., cognitive gateway. Home M2M communications involve body area, personal area and local area wireless access technologies. M2M communications in Body Area Networks (BANs) primarily provides human-centric services ($\leq 2m$). The communications is decomposed into two tiers: intra-BAN communications and inter-BAN communications. Both are typical M2M communications. M2M communications in personal areas target short-range applications in home surroundings ($\leq 10m$). A number of short-range communications standards can be employed for personal areas M2M communications, e.g., Zigbee, Bluetooth, IETF 6LoWPAN, WiFi, and WirelessHART. Local area M2M communications refer to communications between the sub-networks and the external network or the communications among machines in the home-scale area.

B. Machine model

A machine that contains multimedia resources is called a *media device*. The device management and resource management protocols are compatible with the Universal Plug and Play (UPnP) and Digital Living Network Alliance (DLNA) standards. In particular, media devices and their multimedia resources should be announced to the entire network before the multimedia content is transmitted and presented. A description file of the multimedia resources and the media capability are stored inside the media device. Here, media capability represents the media device's ability in managing, controlling, processing and rendering multimedia resources. For instance, multimedia upload, download, push, pull, and print are all typical media capabilities. Each media device should periodically broadcast its description file in the network to announce its multimedia resources and media capability as well. Multimedia services are broadly classified into two categories: resilient and non-resilient services. Resilient services are flexible in QoS requirements; while non-resilient services have hard QoS requirements. Video and data communications are typical resilient services, which are usually tolerant in degraded QoS at some extent. Accordingly, there are two classes of media devices: those capable of providing/processing resilient media, and those only capable of providing/processing non-resilient media.

C. Cross-layer design of rate and admission control

By using cross-layer design approach, we propose a Distributed Rate and Admission Control (DRAC) scheme for QoS provisioning in home M2M networks. In DRAC, each machine contains two important entities: the media format management entity and the QoS management entity. The procedure of DRAC is launched by an initializing media device, which triggers the multimedia sharing in the home M2M network. The initializing media device broadcasts a request message in the network, claiming for the admission to setup a new multimedia session.The request message contains the basic information of the media transmitter and the receiver. Upon receiving the request message, the media player will send out an inquiry message to the media provider asking for full information of the multimedia session property. After obtaining the feedback from the media provider, the media player will firstly invoke the *media format management entity* to examine whether the session property matches its device capability. Thereafter, if the media player finds incapable of providing the required multimedia service, it will notify the initializing media device to directly deny the new session. If the device capability matches the multimedia session, the media format management entity will output a device description file and a media description file to the *QoS management entity*.

The QoS management entity has two key modules: the Queuing Analysis Module (QAM) and Game theory Analysis Module (GAM). In home M2M multimedia sharing, the multimedia services can be categorized into resilient and non-resilient services.The QoS management entity will decide whether the new media flow is acceptable or not based on the result of the QAM. For a resilient media, there are multiple optional rates in the media description file. The QoS management entity will invoke GAM to compete with ongoing media flows for a satisfying rate. More concretely, given the rate of the existing media flows, the GAM will select a tentative rate which could maximize the utility of the new media flow. This tentative rate is then announced in the network through the MAC and PHY layers. Based on the tentative rate of the new flow, each existing media service will invoke its GAM and feedback with an updated rate. From then on, all the media flows (including the new one) will compete under a non-cooperative game theory framework. In the equilibrium state, each media flow obtains the rate with the maximized utility. If there exists a media flow whose QoS requirement (e.g., the delay) is not satisfied, then the new session has to be denied; otherwise, the new flow could be admitted with the resulted rate in the competition. The QoS management entity then informs the media format entity the rate and admission control decision. Accordingly, if the new flow is admitted, the media decoder will prepare for receiving and processing the new media service. The new media player will send an acknowledgement message indicating the accepted rate to the media provider. The end-to-end connection is then built up. If the new flow is denied, the media player will send an acknowledgement message to notify the rejection.

The QAM is integrated with a low-complexity queuing analysis model to estimate the access delay of the media flow. The estimated access delay as well as the accepted rate are combined into a single utility to evaluate the media flow. The GAM is the key to enable distributed operations of DRAC. By casting the problem into the game theory framework, the GAM of the new media player will complete with those of the existing media devices for the wireless bandwidth.

III. Low-Complexity Delay Analytical Model

In this paper, we develop an analytical model for delay of a p-persistent CSMA/CA system,which has I classes of unsaturated stations (class 0 corresponds to the highest priority).The system totally has $\sum_{i=0}^{I-1} n_i$ stations, where n_i represents the number of the i-th class stations. The traffic activities of the i-th class stations follow the Poisson process with mean arrival rate λ_i and departure rate μ_i. In principle, the setting of parameter p in p-persistent CSMA/CA is equivalently to tuning the size of backoff window in CSMA/CA. Hence, by varying the parameter p_i for the i-th class stations, differential QoS provisioning could be easily achieved. Once the channel is sensed to be idle, the station will transmit the head-of-line (HOL) packet with probability p_i when new time slot commences. Otherwise, it will wait until the channel is idle. Suppose a transmission is always successful if no collision. A queuing model is built for each station, which is described by the M/GI/1 model. For simplicity, let us consider the light traffic load condition. Hence, the average output packet rate of the queuing system is equal to the input rate λ_i. Let T_s^j denote the transmission time of a class i station. In a long-term observation, the time fraction that a station of the i-th class occupies the channel is given by $\lambda_i T_s^i$. Let ξ_i represent the time fraction that a class i station may observe that the channel is idle. Then we have

$$\xi_i = 1 - \sum_{j=0, j\neq i}^{I-1} n_j \lambda_j T_s^j - (n_i - 1)\lambda_i T_s^i \tag{1}$$

We know that ξ_i also represents the probability that, in a given slot, the channel is idle for a station of class i. Hence, for a non-empty station of class i, the transmission probability in an arbitrary slot is represented by $\xi_i p_i$. The average service rate of the i-th class of stations μ_i, in the light load condition, is given by

$$\mu_i = \frac{\xi_i p_i}{T_s^i} \tag{2}$$

Let $\rho_i = \frac{\lambda_i}{\mu_i}$ denote the utilization coefficient of the i-th class of stations. Following the M/D/1 queuing model, the queuing delay is then derived by $W_Q^i = \frac{\rho_i}{2\mu_i(1-\rho_i)}$. The average service time W_S^i is the inverse of the average service rate, i.e., $W_S^i = \frac{1}{\mu_i}$. Consequently, the total delay of the i-th class of stations d_i is given by

$$d_i = W_Q^i + W_S^i = \frac{2-\rho_i}{2\mu_i(1-\rho_i)} = \frac{2\mu_i - \lambda_i}{2(\mu_i^2 - \lambda_i \mu_i)} \tag{3}$$

It is noteworthy that, (2) and (3) are the approximate under the light load condition, e.g., $\rho_i \ll 1$.

IV. GAME THEORY FORMULATION AND ANALYSIS

A. *Non-cooperative game formulation*

The rate and admission control process is formulated as a complete information non-cooperative n-player game. The stations in the network contending for packet transmissions are the players. There are I class of stations ($i = 0, 1, \cdots, I-1$, 0 corresponds to the highest priority). In such a game, a player of class i stations selects a rate λ_i in its strategy space $\mathcal{R}_i = (\lambda_{\text{min}}^i, \lambda_{\text{max}}^i)$ to send packets, and then it will gain a payoff according to the selected strategy. The players in the game are assumed to be rational, i.e., always having a tendency to maximize their own utilities by adjusting their strategies. Hereafter, we formulate the rate and admission control problem as a Non-cooperative Rate and admission control Game (NRG), which is represented as $G = [S, \{\mathcal{R}_i\}, \{u_i\}]$, where $S = (1, 2, \cdots, n)$ is the set of game players, Λ_i is the strategy space of the i-th class station, and u_i is the utility function of the i-th user. Players in the game are independent decision makers whose utility depends not only on its own strategy but also the other players' strategies. The key of this non-cooperative game is that the convergence of the strategies should be guaranteed. In other words, the utility function of game players should be well defined to ensure the existence and uniqueness of equilibrium strategies.

B. *Utility function*

We now present the definition of utility (i.e., payoff), which is used to quantitatively describe the players' degree of satisfaction with respect to its action in the game. In the NRG game, all the media devices aim to maximize their transmission rate while minimizing the access delay. Hence,the utility function is defined by

$$u_i = (\lambda_i - \lambda_{i,0}) - w_i(d_i - d_{i,0}) \tag{4}$$

where $\lambda_{i,0}$ and $d_{i,0}$ are the reference transmission rate and the reference access delay for the i-th class of media devices, respectively, and parameter $w_i > 0$ indicates the relative importance weight (delay versus transmission rate) of the i-th class of media devices.

The unified form of utility functions is defined in (4) while tunable parameters allow the provisioning of differential QoS services. The utility function for the media devices with realtime applications, such as voice and video services, will has a larger coefficient w_i and a smaller reference delay $d_{i,0}$. On the contrary, those with non-realtime applications, such as email, http services, the utility function will have a smaller w_i and a larger $d_{i,0}$. By combining (2), (3) and (4), we obtain the explicit expression of the utility function

$$u_i = \lambda_i + \frac{w_i T_s^i (T_s^i \lambda_i - 2p_i \xi_i)}{2p_i[p_i \xi_i + T_s^i \lambda_i]\xi_i}. \tag{5}$$

From (5),We know the utility function is actually a function of the transmission rate λ_i's of all the media flows. Let Λ_{-i} denote the set of strategies (actions) of the other media devices. The utility function of the i-th class of media devices could be written as $u_i(\lambda_i, \Lambda_{-i})$.

C. *Existence and uniqueness of Nash Equilibrium*

In a non-cooperative game, the Nash equilibrium (NE) is a stable state with a strategy profile, in which no game player has incentive to deviate. In the NRG game, we are interested in the following questions: i) do there exist NEs? ii) if so, is it unique and can players converge to the NE? We will answer these two questions through the following analysis.

In general, NE does not necessarily exist in a game.The existence of NE can be proved by validating that the strategy space of each player is a non-empty compact and convex set of Euclidean space $\mathbb{R}^n$ and $u_i(\lambda_i, \Lambda_{-i})$ is continuous for $\{\lambda_i, \Lambda_{-i}\}$ and quasi-concave in λ_i [6]. To prove the uniqueness of NE, we validate that the best response function of each game player with respect to strategy s_i is a standard function [7]. The best response function can be obtained by solving $\frac{\partial u_i}{\partial \lambda_i} = 0$. Substituting (3) into (4) and computing the derivation over λ_i yields

$$\frac{\partial u_i}{\partial \lambda_i} = \frac{p_i^2 \xi_i^2 - 2p_i T_s^i \lambda_i \xi_i + T_s^{i2} \lambda_i^2 - 1/2 w_i T_s^{i2}}{[p_i \xi_i - T_s^i \lambda_i]^2} = 0 \tag{6}$$

by solving which we get two roots. By eliminating the negative root, we obtain the best response by

$$r_i = \frac{p_i \xi_i + \sqrt{\frac{1}{2} w_i} T_s^i}{T_s^i}. \tag{7}$$

Theorem 1: A Nash Equilibrium exists in the NRG game $G = [S, \{\Lambda_i\}, \{u_i\}]$, if all $i \in S$.

Proof:

i) It is clear that the strategy space $\mathcal{R}_i$ =$[\lambda_{min}^i, \lambda_{max}^i]$ is non-empty and is compact for it is a bounded closed set. For the convex characteristics, $\forall\ x_1, x_2 \in \mathcal{R}_i = [\lambda_{\min}^i, \lambda_{\max}^i]$, $\theta \in [0, 1]$, $\theta x_1 + (1 - \theta) x_2 \in \mathcal{R}_i$ always holds. Therefore, $\mathcal{R}_i$ is a convex set of $\mathbb{R}^n$.

ii) Consider the expression of u_i in (5).u_i is surely continuous in $\{\lambda_i, \Lambda_{-i}\}$. Regarding the second order derivative with respect to λ_i, we have

$$\frac{\partial^2 u_i}{\partial \lambda_i^2} = \frac{-w_i T_s^{i3}}{(p_i \xi_i - T_s^i \lambda_i)^3}. \tag{8}$$

Under a non-saturated network, the constraint condition $\rho_i = \frac{\lambda_i}{\mu_i} < 1$ holds, which leads to $\lambda_i < \xi_i p_i / T_s^i$. By transition, we have $\xi_i p_i - T_s^i \lambda_i > 0$, which indicates that the second derivation of u_i is negative. This means that, u_i is a concave function (and therefore quasi-concave) in λ_i. According to [6], a Nash equilibrium is proven to exist in the NRG game.

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Theorem 2: The game NRG has a unique equilibrium.

Proof: Let Λ denote the Nash equilibrium in the NRG. The Nash equilibrium should satisfy $\Lambda = \mathbf{r}(\Lambda)$, where $\mathbf{r}(\Lambda) = (r_1(\Lambda), r_2(\Lambda), \cdots, r_n(\Lambda))$, $r_i(\Lambda)$ is the best response function of the i-th class of media devices as shown in

$$r_i(\Lambda) = \max\left\{\lambda_{\min}^i, \min\left\{\lambda_{\max}^i, \frac{p_i \xi_i + \sqrt{\frac{1}{2} k_i} T_s^i}{T_s^i}\right\}\right\}. \tag{9}$$

The uniqueness of NE is proven by validating that the best response function is a standard function. A function is said to be standard if it satisfies the following properties:

- *Positivity:* $\mathbf{r}(\Lambda) > 0$. As mentioned before, $\xi_i > 0$, it is easy to verify that the best-response function is always positive.
- *Monotonicity:* If $\Lambda \geq \Lambda'$ then $\mathbf{r}(\Lambda) \geq \mathbf{r}(\Lambda')$. The best-response function is the positive root of a quadratic function, as shown in (7). The quadratic function $\frac{\partial u_i}{\partial \lambda_i} = 0$ has U relationship with the $\mathbf{r}(\Lambda)$. As a consequence, in the right side of the positive root is definitely monotony.

TABLE I
SIMULATION PARAMETERS FOR THE FOUR MULTIMEDIA SESSIONS.

Session number (i)	1	2	3	4
Media Type	Audio-1	Audio-2	Video-1	Video-2
Traffic model	Poisson	Poisson	Poisson	Poisson
Packet size	192B	192B	600B	600B
Full source rate	64kbps	64kbps	7.5Mbps	7.5Mbps
CSMA parameter	0.08	0.08	0.05	0.05

- *Scalability:* $\forall \varepsilon > 1$, $\varepsilon \mathbf{r}(\Lambda) > \Lambda(\varepsilon\Lambda)$. $\forall i$, we have

$$\varepsilon r_i(\Lambda) - r_i(\varepsilon\Lambda) = \frac{p_i(\varepsilon - 1) + \sqrt{\frac{1}{2} w_i} T_s^i (\varepsilon - 1)}{T_s^i} \tag{10}$$

Clearly, for $\forall \varepsilon > 1$, we have $\varepsilon r_i(\Lambda) - r_i(\varepsilon\Lambda) > 0$.
The properties of positivity, monotonicity and scalability are verified, which justify that the NRG has a unique NE.

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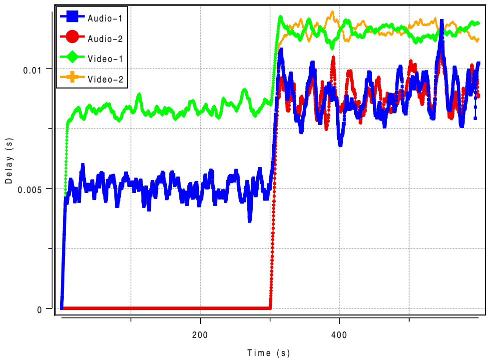
V. PERFORMANCE EVALUATION

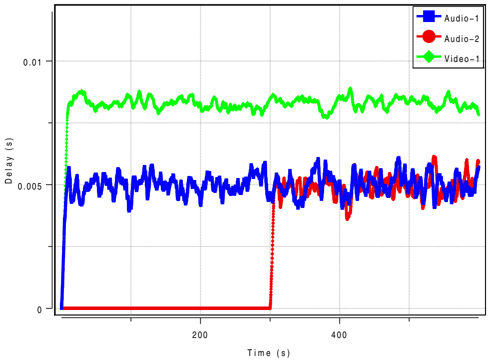
In this section, we evaluate the performance of DRAC in a home M2M networking environment through simulation. Media devices access to the wireless resource for multimedia sharing in a p-persistent CSMA/CA manner here. The total wireless bandwidth is 11Mbps, and the size of time slot is 20μs. The buffer length of each media device is 50 packets. Each multimedia service is transmitted directly from the media provider to the media player. The parameter setting of all the multimedia sessions in the simulation is described in Table I. In the first 300s, Audio-1, Video-1 are running at full rates. After that, Audio-2 and Video-2 are triggered.

Fig. 1 shows the performance comparison in terms of access delay. From Fig. 1(a), we observe that the delay of Audio-1 changes from 4ms to 11ms, and that of Video-1 changes from 8ms to 12ms when the new audio and video sessions directly access to the network without rate adaption. In Fig. 1(b), only with admission control, the delay of Audio-1 and Video-1 remain almost unchanged since the new video session is rejected due to admission control. Fig. 1(c) shows that, in DRAC, the delay of Audio-1 changes from 4ms to 8ms and that of Video-1 remains almost unchanged at 8ms although new audio and video sessions are admitted into the network. These results indicates the presence of admission control protects the ongoing video sessions, but denies the new ones. In DRAC, the new video session can be accepted while the delay of the video sessions remains at a satisfying low level.

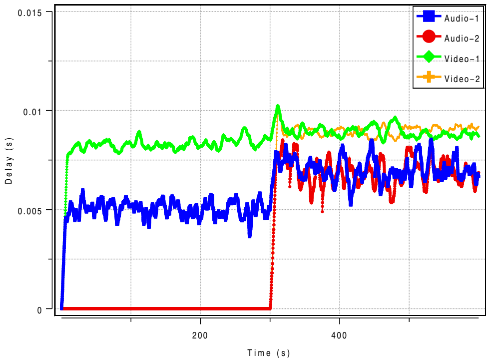
Fig. 2 shows the performance comparison in terms of transmission rate. In Fig. 2(a), the actual average rate of Video-1 degrades from 7.5Mbps to 5.2Mbps after the new audio and video is admitted. In addition, the average rate of Audio-1 in the last 300s is significantly lower than that in the first 300s. In Fig. 2(b), with only admission control, the actual average rate of Video-1 and Audio-1 remain almost unchanged since the new video is rejected. In Fig. 2(c), the source rate of the Video-1 and Video-2 are both tuned from 7.5Mbps to 5Mbps. The transmission rate of Audio-1 remains nearly unchanged in the last 300s. These results reveal that, the actual transmission rate of the audio and video sessions may not be guaranteed if there



(a) Delay in the scheme without rate or admission control.



(b) Delay in the scheme with only admission control.



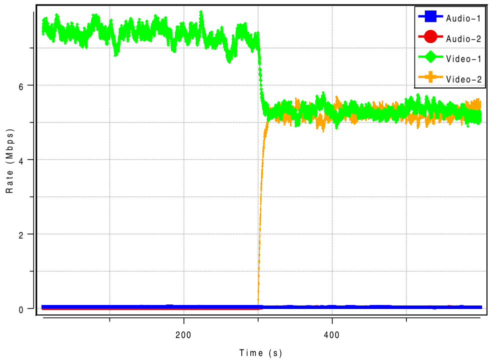
(c) Delay in DRAC.

Fig. 1. Delay under different schemes.

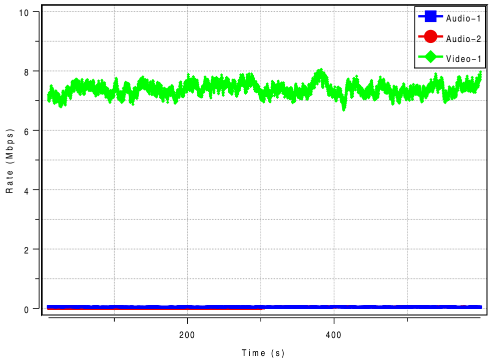
is no appropriate admission and rate control. By moderately reducing the source rate of video sessions, DRAC is able to flexibly handle the service rate of realtime sessions.

VI. CONCLUSIONS

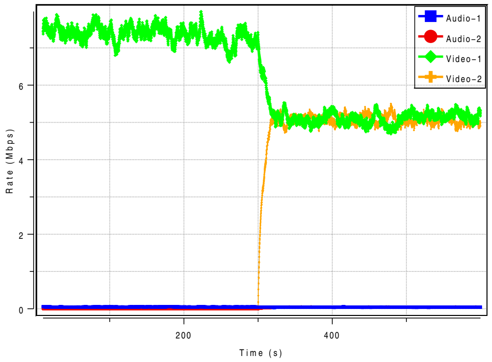
In this paper, we focused on resilient QoS management in home M2M networks. A cross-layer optimized Distributed Rate and Admission Control (DRAC) scheme is proposed for multimedia sharing. DRAC has a game theory framework for home machines to analyze and predict the QoS performance, and adaptively regulate the source rate to accommodate more media sessions without significant QoS degradation. Simulation results indicate that DRAC is an efficient scheme to facilitate the distributed allocation of radio bandwidth based on QoS demands in resource-constrained home M2M networks.



(a) Throughput in the scheme without rate or admission control.



(b) Throughput in the scheme with only admission control.



(c) Throughput in DRAC.

Fig. 2. Throughput in different schemes.

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