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A Dynamic Bandwidth Reservation Scheme for Hybrid IEEE 802.16 Wireless Networks

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***Abstract*—A dynamic bandwidth reservation (DBR) scheme for hybrid IEEE 802.16 wireless networks is investigated, in which 802.16 networks serve as the backhaul for client networks, such as WiFi hotspots and cellular networks. The DBR scheme implemented in the subscription stations (SSs) (co-locating with access pointers) consists of two components: connection admission controller (CAC), and bandwidth controller (BC). The CAC processes the received connection set-up requests from the client networks connected to the SSs. The BC manages the request and release of bandwidth from the base station (BS). It dynamically changes the reserved bandwidth between a small number of values. Hysteresis is incorporated in bandwidth release to reduce bandwidth request signalling load and connection blocking probability. An analytical model is proposed to evaluate the performances of reserved bandwidth, connection blocking probability and signalling load. The impacts of hysteresis mechanism and probability of reservation request blocking are taken into account. Simulation verifies the analytical model.**

I. INTRODUCTION

IEEE 802.16 standards have been developed for metropolitan broadband wireless access (BWA) systems [1]. With high data rate, large network coverage and excellent Quality of Services (QoS) capabilities, 802.16 networks can offer a wide variety of applications [1] [2], e.g. high-speed Internet access, enterprize business applications, backhaul for WiFi hotspots, cellular networks, and public safety services networks. In this paper, we will consider the application of 802.16 networks as backhaul for the so-called clients networks, such as WiFi hotspots and cellular networks. For this application, a certain amount of bandwidth will be required by the client networks to provide QoS and reduce blocking probability.

The required bandwidth for the QoS traffic can be requested on demand or reserved in advance. IEEE 802.16 standard specified three classes of connections to support QoS traffic, which differ on the required QoS by the applications supported on these connections [1] [2]. The QoS connections can use different mechanisms to request and change bandwidth on demand with the BS. These mechanisms are flexible and can work well with subscription stations (SSs) supporting a few number of QoS connections. However, for the hybrid SSs (HSSs) which serve as backhaul for client networks, the frequency of activating and terminating connections can be very high, which incurs a high cost in terms of bandwidth request signalling and provisioning. The cost will be more significant in 802.16 mesh network scenarios. Another problem that may arise for the HSSs is the possibly high and unacceptable connection blocking probability to the operators of the client networks connected to the HSSs. An alternate method which may solve this problem is by reserving bandwidth in advance instead of requesting bandwidth on demand.

In this paper, we evaluate and optimize a DBR scheme with hysteresis for the HSSs in the hybrid IEEE 802.16 networks. The motivations are to evaluate its performance and effectiveness for the hybrid network, and find efficient methods to ensure optimum reservation and utilization of bandwidth while minimizing signal blocking probability and signalling cost. An analytical model is proposed for the purpose of performance evaluation. The impact of the probability of request being blocked are investigated which has not been considered in the earlier literature [4] [5] [6] [7]. In the rest of the paper, related work will be introduced in Section II. DBR scheme will be presented in Section III. The Markov model is proposed to analyze the performances of DBR scheme in Section IV. Numeric results are presented in Section V.

II. RELATED WORK

In the current literature, there are many references to mechanisms and methods for dynamic bandwidth reservation in a system consisting of one or multiple traffic classes. Orda *et al* investigated a DBR scheme with fixed reservation thresholds and hysteresis on bandwidth release for bandwidth allocation to virtual paths (VPs) [4]. A heuristic method is proposed to determine the reservation thresholds. A Markov chain model is proposed to investigate the performance of the DBR scheme. DBR schemes with and without hysteresis are investigated for bandwidth allocation to virtual paths (VPs) [5] . The schemes are evaluated by Markov chain model as well and optimized under the constraits on request processing capability at the link controller. However, in the multiple VP bandwidth allocation problem, the Markov chains for the VPs are developed from the single VP network scenario. This development does not accurately model the DBR schemes, and will introduce inaccurate to performance evaluation and algorithm design.

A hysteresis mechanism is proposed in [6] for optimal resources allocation in ATM networks. This mechanism combines the processes of connections management, dynamic rate allocation and flow control. The change of bandwidth is made

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based on the state of the client queue at ATM switch. A Markov model is developed to evaluate the performance of the mechanism. A similar mechanism to that of [6] is investigated by Gakhar *et al* in [7] for DBR in IEEE 802.16 networks. Markov chain model is proposed for DBR with hysteresis and used for performance optimization.

In the above multi-thresholds based DBR schemes, the possibility of bandwidth request blocking is only considered in the analytical model proposed in [4]. For example, the DBR scheme model is proposed for only one HSS in the IEEE 802.16 network. Unfortunately, the model in [4] has very high computation complexity and can be used for only a few VPs. The problem will be investigated later in this paper.

In addition to the DBR schemes, there are several multiple guard channel (MGC) solutions proposed for the session admission control in the cellular networks with differentiated sharing of wireless network bandwidth [8] [9] [10]. However, it is noted that all the session admission control and parameter configurations are implemented in the cellular base station. In the 802.16 DBR scheme, the functions of DBR and parameter configuration will be distributed to the HSSs; the HSSs need request bandwidth from the BS. Another difference is that the thresholds in the MGC schemes are used to differentiate bandwidth sharing among different classes of traffics, while bandwidth is reserved by HSSs for exclusive usage.

III. Dynamic Bandwidth Reservation Scheme

A. Network Scenario

As stated in the introduction in Section I, we consider the application of 802.16 network to act as backhaul for or connecting client networks, e.g., WiFi hotspots, cellular networks and enterpriser business networks. The 802.16 network and client networks forms a hybrid 802.16 network. The 802.16 network can be operated in Point-to-MultiPoint (PMP) mode. To increase network coverage, the 802.16 network can also be operated in mesh mode by multihop networking.

An illustrative hybrid 802.16 networks is shown in Fig.1. The 802.16 network is operated in a PMP mode. In the investigated network architecture, the HSSs collects traffic from one or several access points of clients networks. The collected traffic are delivered to the BS. Then the BS forwards traffic from the HSSs to Internet, mobile switch center for cellular networks, or another type of wireless networks. It is expected that the number of connections can be very large and dynamically changed in the clients network (e.g., mobile phone users in cellular networks). If no bandwidth is reserved in a HSS, the HSS need request or release bandwidth from the BS frequently every time a QoS connection is activated or terminated at the access points. The associated signalling and processing load between the BS and HSSs can be significant, especially when the 802.16 network is operated in mesh mode. Therefore, it makes sense to limit the signalling and processing loads by implementing DBR that is seldom modified, but can still support QoS traffic.

The DBR scheme investigated here allows to operate with a minimum amount of reserved bandwidth when the actual load is small, while seamlessly reserve the necessary amount of resources when the actual load significantly increases. It mainly consists of two components: connection admission controller (CAC), and bandwidth controller (BC). The CAC processes the received connection set-up requests from the stations connected to the HSSs. The BC manages the request and release of bandwidth. To minimize the reserved bandwidth, the BC monitors the available bandwidth and the number of admitted connections, and dynamically changes the amount of reserved bandwidth between a small number of values. The cost in term of reserved resources can be optimized together with the reduction in signaling. However, the selection of the optimum set of parameters depends on expected offered load, as well as the costs of reserved bandwidth and signalling.

In the DBR scheme, the reservation values are chosen based on reservation thresholds, pre-determined for a target traffic class, e.g. on the basis of the busy hour offered load. But the scheme can also operate at a significantly lower load. If the operators of client networks prefer to use only one fixed bandwidth reservation, they have to choose between reserving a large amount of resources based on the busy hour offered load at the risk of low bandwidth utilization, or reserving a significantly smaller amount of resources at the risk of QoS degradation.

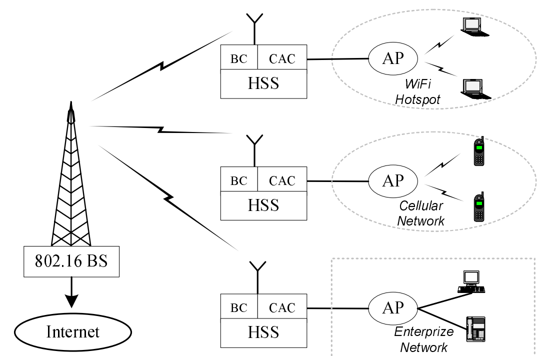

Fig. 1. Hybrid IEEE 802.16 network architecture.

B. Bandwidth Reservation Schemes

The dynamic bandwidth reservation schemes can be classified into two types: with or without hysteresis. For simplicity, let DBR-H and DBR-NH denote the DBR schemes with and without hysteresis, respectively. Both types of DBR schemes can be characterized with a set Ω_{rv} of reservation thresholds, Ω_{rv}=$\{B_r, r = [1, ..., m]\}$ with $B_r < B_{r+1}$, for $r \in [1, m-1]$. The thresholds in the set of Ω_{rv} is also called reservation states of a HSS. The reserved bandwidth for a HSS will vary among the thresholds according to the bandwidth utilized by the clients. As proved in [5], an optimal threshold policy for the DBR schemes must be (almost) deterministic, which means once the thresholds in Ω_{rv} are chosen, they will be fixed as thresholds instead of selecting to be thresholds with probabilities in stochastic threshold policy. Therefore only fixed threshold DBR schemes are considered in this paper.

In the DBR-NH scheme, if a connection request arrives at a time when the number of admitted connections (denoted by N_c) in a HSS reaches a threshold B_r in Ω_{rv}, $r \in [1, m-1]$, the HSS will request to the BS to reserve B_{r+1} bandwidth. If the request is approved, the reserved bandwidth B_r at this HSS is changed to B_{r+1}, otherwise remains unchanged. On the other hand, in the case of the reserved bandwidth of a HSS being B_i ($i \in [2, m]$), if the admitted connection reduces to the threshold B_{r-1}, then the HSS will request to release a part of bandwidth and change the reserved bandwidth B_r to B_{r-1}. It is noted that the reservation thresholds in the DBR-NH scheme act as both bandwidth request and release points for reserved bandwidth. Reserved bandwidth may vibrate frequently [5].

DBR-H scheme is proposed to avoid the vibration situations, reduce the signaling cost and minimize the impacts of delay in request processing. In the DBR-H scheme, each reservation state B_r ($r \in [1, m]$) in Ω_{rv} is associated with a release threshold A_r as the bandwidth release point for B_r, with $A_r < B_r$. Let Ω_{rl} denotes the set of release thresholds A_r, $r \in [1, m]$. Unlike in the DBR-NH scheme where the release point A_r (associated with reservation state B_r) equals to B_{r-1} ($i \in [2, m]$, A_r is set to no larger than B_{r-1}+1 in the DBR-H scheme. Therefore the signalling cost for bandwidth reservation and allocation can be reduced. The reduction of signalling cost is obtained at the cost of reserved bandwidth.

IV. Analytical Model

A. Model Assumption

This section discusses an analytical model for the DBR-H scheme for a hybrid IEEE 802.16 network. The number of reservation states is m and $A_1 = 0$. In the 802.16 network, a BS serves N_s HSSs. The 802.16 network is assumed to be operated PMP mode. But the proposed analytical model can be extended to mesh mode. We consider the following hypothesis:

- The arrival of connections in HSSs is a Poisson process with a common rate of λ.
- The service times of connections are independently and identically distributed (i.i.d) exponential random variables with a common parameter of μ. Service times are independent of arrival times.
- The connections have a QoS requirement of 1 bandwidth unit per connection.
- The bandwidth of 802.16 wireless network allocated to the QoS connections is B_c units. The left capacity can be used for other types of traffic.
- No waiting space is available, which means if a connection arrives when the reserved bandwidth in a HSS is all occupied, the connection will be dropped.

The above hypothesis on connection arrival and service time are common in the systems where a large number of potential users initiate identical real time multimedia communications. The model then applies to the case where the target QoS connections are of this type. The model extends easily to several types of QoS connections, without modifying the qualitative behavior of the system.

B. Steady State Equations

Let $B(t)$ and $N(t)$ denote the reserved bandwidth and the number of admitted connections at time t in a HSS, respectively. Denote by Π_{B_r,N_c} the stationary probability distribution of $\lim_{t\to\infty} B(t)$=B_r and $\lim_{t\to\infty} N(t)$=N_c. Let ρ_r denote the probability that a bandwidth request from a HSS with reserved bandwidth being B_r will be unsuccessful due to insufficient bandwidth in the BS, $r \in [1, m-1]$. Then the stationary distribution Π_{B_r,N_c} of the DBR states (B_r, N_c) can be described by the Kolmogorov's forward equations. By considering the system as a dynamic flow, the forward equations can be written as a simple but useful flow diagram in Fig.2, under a simple principle that flow rate into a state equal to the flow rate out a state. The balance equations for the states will be described in details as follows.

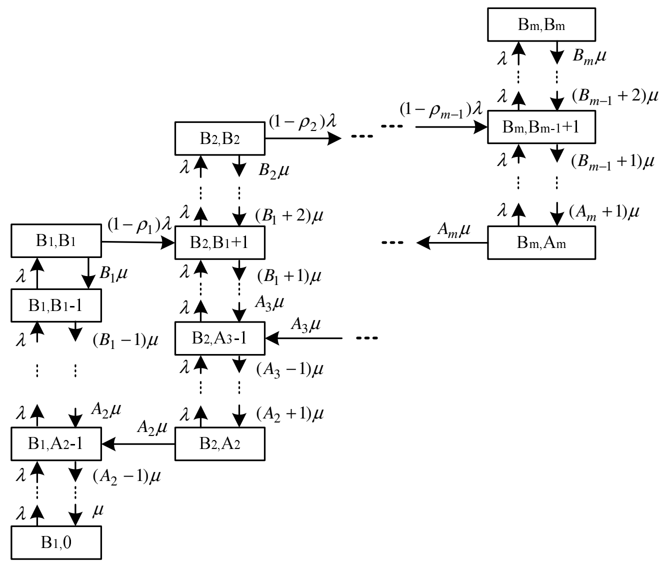

Fig. 2. Markov chain for the DBR-H scheme.

Simply, for the state $(B_1, 0)$ (note that A_1=0), the balance equation is:

$$\lambda\Pi_{B_1,0} = \mu\Pi_{B_1,1}. \tag{1}$$

Similarly, we have balance equation for the state (B_m, B_m):

$$B_m\mu\Pi_{B_m,B_m} = \lambda\Pi_{B_m,B_m-1}. \tag{2}$$

The balance equations for the states at the bandwidth reservation points are described by:

$$[(1-\rho_r)\lambda + B_r\mu]\Pi_{B_r,B_r} = \lambda\Pi_{B_r,B_r-1}, r \in [1, m-1]. \tag{3}$$

The left side of Equation (3) means that if an admitted connection is finished, or a connection request arrival and bandwidth request to the BS is granted at the bandwidth reservation point, then the HSS state at the bandwidth reservation points will be changed.

Similarly the balance equations for the states at the bandwidth release points are described by:

$$(\lambda + A_r\mu)\Pi_{B_r,A_r} = (A_r+1)\mu\Pi_{B_r,A_r+1}, r \in [2, m]. \tag{4}$$

For any state (B_r, N_c) with reserved bandwidth being B_r and the state not being the bandwidth reservation and release points, we have balance equations:

$$(\lambda + N_c\mu)\Pi_{B_r,N_c} = (N_c+1)\mu\Pi_{B_r,N_c+1} + \lambda\Pi_{B_r,N_c-1}, \tag{5}$$

where $r \in$ [1,m-1], $N_c \in$ [A_r+1,B_r-1], $N_c \neq A_{r+1}$-1 and $N_c \neq B_{r-1}$+1.

For the states to which the states at the bandwidth reservation point will be changed after a bandwidth request is granted, we have the following balance equations:

$$\begin{aligned}&[\lambda + (B_{r-1}+1)\mu]\,\Pi_{B_r,B_{r-1}+1} = (B_{r-1}+2)\mu\Pi_{B_r,B_{r-1}+2} + \\ &\lambda[(1-\rho_{r-1})\Pi_{B_{r-1},B_{r-1}} + \Pi_{B_r,B_{r-1}}], r \in [2,m].\end{aligned} \tag{6}$$

Similarly, for the states to which the states at the bandwidth release point will be changed to after bandwidth is released, we have the following balance equations:

$$\begin{aligned}&[\lambda + (A_{r+1}-1)\mu]\,\Pi_{B_r,A_{r+1}-1} = \lambda\Pi_{B_r,A_{r+1}-2} + \\ &A_{r+1}\mu(\Pi_{B_r,A_{r+1}} + \Pi_{B_{r+1},A_{r+1}}), r \in [1,m-1].\end{aligned} \tag{7}$$

So far we have obtained balance equations for each of the state (B_r, N_c) shown in Fig.2. However the balance equations are not linearly independent and will become so by dropping one of them, for example equation (1) or (2). Then with the normalizing equation:

$$\sum_{r=1}^{m} \sum_{N_c=A_r}^{B_r} \Pi_{B_r,N_c} = 1, \tag{8}$$

the stationary probability distribution Π_{B_r,N_c} can be obtained, if the request blocking probability ρ_r are known for $r \in [1,m]$.

Under the assumption that all the HSSs are identical and independent, a simple analytical method can be used to calculate ρ_r, which can be used with the above balance equations to solve the stationary distribution Π_{B_r,N_c}. Let p_r be the probability that the reserved bandwidth in an HSS is B_r in steady state, $r \in [1,m]$. We have

$$p_r = \sum_{N_c=A_r}^{B_r} \Pi_{B_r,N_c}, \tag{9}$$

and

$$\sum_{r=1}^{m} p_r = 1. \tag{10}$$

Let V_n be a random variable representing the reserved bandwidth in the nth HSS, $n \in [1, N_s]$. For all the HSSs, V_n has identical independent probability distributions. It can be observed that once the reservation thresholds are given, the steady state probability Π_{B_r,N_c} and p_r can be expressed as functions of ρ_r, $r \in [1,m]$. In return, the variables ρ_r can be expressed as functions of p_r.

$$\rho_r = prob(\sum_{n=2}^{N_s} V_n > B_c - B_{r+1} + B_r), r \in [1, m-1]. \tag{11}$$

Due to the complexity of calculating p_r, a distributed DBR optimization scheme has been proposed, in which p_r can be provided by the BS to the HSSs. Due to limited space, the distributed DBR optimization scheme is not presented here. The balance equations for the DBR states can then be resolved by numerical techniques to calculate network performances.

C. Network Performance

Once the stationary probability distribution for the DBR states are obtained, the average reserved bandwidth in one SS (denoted by B_{rsv}) can be calculated by:

$$B_{rsv} = \sum_{r=1}^{m} p_r B_r. \tag{12}$$

Let R_t denote average transition rate, which is defined as the number of changes of the reserved bandwidth in a HSS in one second. The average transition rate R_t is calculated by:

$$R_t = \sum_{r=1}^{m-1} \lambda\Pi_{B_r,B_r} + \sum_{r=2}^{m} A_r\mu\Pi_{B_r,A_r}. \tag{13}$$

Let p_b denote the the average connection blocking probability, which is calculated by:

$$\begin{aligned} p_b &= \frac{\sum_{r=1}^{m-1} \rho_r\lambda\Pi_{B_r,B_r} + \lambda\Pi_{B_m,B_m}}{\lambda} \\ &= \sum_{r=1}^{m-1} \rho_r\Pi_{B_r,B_r} + \Pi_{B_m,B_m}. \end{aligned} \tag{14}$$

As DBR-NH scheme can be treated as a specific case of DBR-H scheme with A_i=B_{i-1}+1, $i \in [2,m]$, the above analytical model for DBR-H scheme is ready to be used for DBR-NH scheme.

V. Numerical Results

In this section, typical analytical and simulation results will be presented. A discrete-event simulator has been implemented for the DBR scheme to validate the analytical model. Each simulation runs for 10000 seconds and 10 simulation results are averaged to obtain one simulation value. In all the experiments, the number of SSs N_s in the network is 10. The overall bandwidth B_c allocated for the DBR scheme in the BS is 50 units. The service time related parameter μ=1 for all the SSs. Let ϕ denote the aggregate network traffic load, which is defined by ϕ=$N_s\lambda/\mu$ with a common connection arrival rate λ for all the SSs. Therefore for each aggregate traffic load, λ can be determined by $\mu\phi$/N_s.

Fig.3, Fig.4 and Fig.5 presents the analytical and simulation results of average reserved bandwidth, call blocking probability and average transition rate of the DBR scheme versus aggregate traffic load ϕ, respectively. The number of bandwidth thresholds in the DBR scheme is configured with m=1 and m=4. Note that when m is set to 1, the DBR scheme will use fixed bandwidth reservation (FBR) instead of dynamic reservation. However, we used "DBR with m=1" as FBR exchangeably for ease of notation. It can be observed the analytical results match perfectly with the simulation results.

In Fig.5, the transition rate of DBR scheme with m=1 is zero, which is obvious as the reserved bandwidth does not change dynamically. It is also shown that DBR scheme with m=4 achieves less reserved bandwidth and lower connection blocking probability than that with m=1. This is reasonable as DBR scheme with multiple reservation thresholds can adaptively adjust bandwidth reservation states and improve bandwidth utilization. However, it is noted that the results presented in Fig.3, Fig.4 and Fig.5 are not optimal for neither the DBR scheme with m=1 nor the scheme with m=4. Instead, the bandwidth reservation thresholds for both schemes are configured by a heuristic method as shown in (15):

$$\begin{cases} B_1 = min(\lfloor \frac{B_c}{1.2N_s} \rfloor, max(1, \lfloor min(\frac{B_c}{m}, 2\lambda) \rfloor)), \\ B_r = rB_1, r \in [2, m], \\ A_1 = 0, \\ A_r = B_{r-1} - 2, r \in [2, m], \end{cases} \tag{15}$$

where functions $min(x, y)$ and $max(x, y)$ calculate the minimum and the maximum of x and y, respectively. The configuration method is used only for the model validation purpose. An optimal configuration can be obtained by searching over the possible configurations and choosing the one resulting in the best network performances.

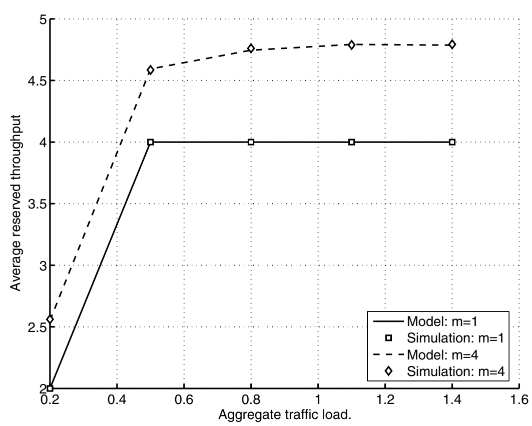

Fig. 3. Average reserved bandwidth in one SS (B_{rsv}) versus aggregate traffic load ϕ.

VI. CONCLUSION

In this paper, a dynamic bandwidth reservation scheme was investigated for hybrid 802.16 wireless networks. The performances of average reserved bandwidth, connection blocking probability and signalling cost are analytically modeled. The impact of bandwidth request blocking probability is taken into account in the analytical model. Simulations show that the model has high accuracy. In our future work, we will present a distributed DBR optimization scheme which can improve bandwidth utilization, call blocking probability and scalability.

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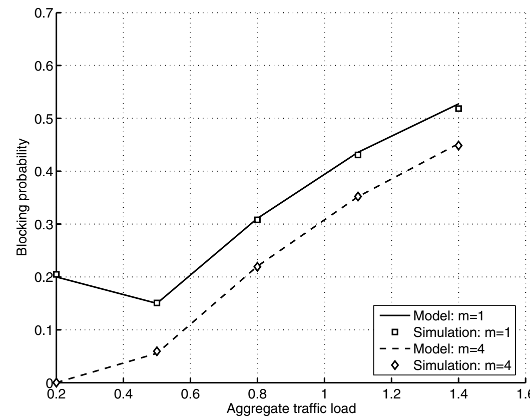

Fig. 4. Average blocking probability p_b versus aggregate traffic load ϕ.

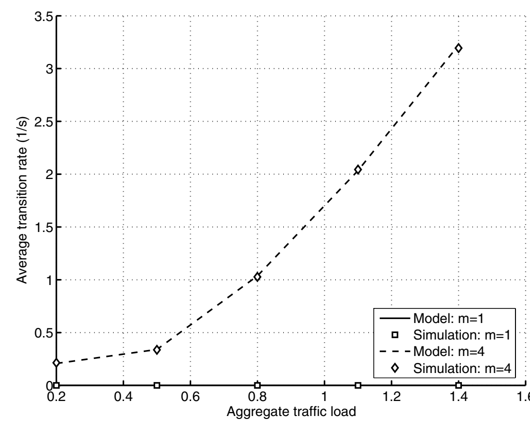

Fig. 5. Average transition rates (number per second) R_t versus aggregate traffic load ϕ.

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