Cross-Layer Cut-Through Switching Mechanism for IEEE 802.16d/e Wireless Networks

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***Abstract*—This paper proposes a fast *cross-layer cut-through switching mechanism (CCSM)* for supporting media access control (MAC) layer packet switching in IEEE 802.16-based broadband wireless access (BWA) networks. The local traffic, which means subscriber stations (SSs) communicating with each other within the *cell*, can be switched via the MAC layer without involving the network layer. The average access delay of request from SSs is studied and analyzed in this paper. Finally, the simulation and numerical results show that the performance of CCSM is superior to that of the legacy IEEE 802.16d/e protocol.**

***Index Terms*—Cross-layer, MAC, network, switching, wireless.**

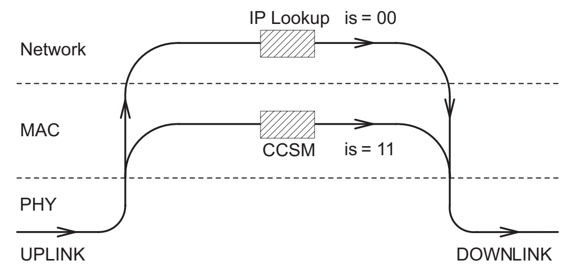

Fig. 1. The process of two-stage cut-through switching mechanism.

I. Introduction

All PACKETS in computer networks are first looked up to find their destinations in the network layer for packet relaying/forwarding. In IEEE 802.16d/e [1] wireless networks, the base station (BS) is used as a role of router/gateway to process packets from/to Internet to/from its subscriber stations (SSs) or mobile SSs (MSSs) [2]. This mechanism, however, will cost a lot of overheads even if the traffic is local, i.e., SSs communicate with each other within the coverage area of a BS. The local traffic will greatly degrade the system performance when the transmitted data is heavy. To avoid this problem, the packets, which are destined for Intranet, i.e., local traffic, can be switched in the medium access control (MAC) layer without disturbing the network layer during the IP lookup process as shown in Fig. 1. All packets (referred to frames) can be efficiently switched in the MAC layer if a *cross-layer switching* mechanism is adopted. In this paper, we point out this problem and propose a cross-layer cut-through switching mechanism (CCSM) to offer a fast data-link layer switching in the IEEE 802.16-based wireless network.

The CCSM uses the reserved bits of the MAC header specified in the IEEE 802.16 standard to identify whether the transported data is in the outgoing traffic or in the turnaround traffic, i.e., the traffic from one SS to another SS inside the service range of the BS. This traffic can quickly go through the MAC layer if it can be identified by the BS. According to the transfer connection identifier (TCID) and some indication bits, which are specified in the MAC header [1] of each MPDU transmitted from the SS, the BS can maintain a label[1] switching table for frames switching in the MAC layer. The BS can quickly determine the next hop TCID for data transmission and examine its corresponding service flow ID (SFID) for the quality-of-service (QoS) scheduling. By doing so, the local traffic can be efficiently transferred in the local area network (LAN) without interfering with the network layer, and thus enhance the system performance.

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II. Cross-Layer Cut-Through Switching Mechanism

The CCSM uses two reserved bits of the generic MAC header called the i-bit and s-bit to notify the BS for layer 2 frame switching operations, where i-bit is used for Internet or Intranet traffic indication and s-bit is used for the request of cut-through switching forwarding or new entry establishment for this connection. First, if the traffic is outgoing, i.e., to the Internet, the SS will send these packets with a TCID and set the i-bit as 0. As the BS receives the burst data, it will be notified by the i-bit that these packets are outgoing and thereby deliver them to the higher layer, e.g. the convergence sublayer (CS), for unpacking or defragmentation operations and further IP lookup. Otherwise, this traffic is local and will be transferred by label switching.

When the traffic is local and transferred for the first time, e.g., an SS within the cell, the is-bit shall be set as 10. It means that the burst data with the TCID has not been set up yet in the label switching table. The BS, then, will forward the data to the network layer for IP lookup and create a TCID (source) to TCID (destination) mapping record in the label switching table for switching usage. Afterward, the SS can send data to the same destination with coded is-bit as 11. When the s-bit is set as one, it means that the TCID mapping record has been built up and the following data will be switched directly. The SS will keep this TCID as a reference for the destination MAC address.

[1]The term 'label' corresponds to the TCID in this paper.

III. Performance Analysis

Assume SSs are connected to a centralized BS over wireless fading channels, where multiple connections (data flows) are supported by SSs. The uplink resource allocation process of the IEEE 802.16 system can be treated as a multiserver $M/M/m$ model: Arrivals are Poisson with rate λ (the average number of SSs per frame). There are m servers, and each of them has an independently and identically distributed exponential service-time distribution with mean $1/\mu$ (the average number of frames an SS requires from the resource). Let C denote the capacity of the resource of uplinks (the number of slots per frame). Based on the call admission control (CAC) rules, each SS is allowed to have the resource of mean k slots per frame for transmission if it is given permission to enter the system. The model satisfies the condition $C \geq mk$. We let $r = \lambda/\mu$ be the offered work load rate and $\rho = r/m = \lambda/m\mu$ be the offered work load rate to a server.

According to the $M/M/m$ model, we utilize the previous theory developed for birth-death processes [3] with steady-state probabilities to get the expected queue size $L_q = \left[r^m \rho/m!(1-\rho)^2\right] p_0$, where p_0 represents the probability of zero number of the SS access the system and is equal to $1/[(r^m/m!(1-\rho) + \sum_{n=0}^{m-1} r^n/n!]$, where $\rho < 1$. To find the expected steady-state system waiting time T, we use the queueing delay T_q and the Little's formulas, $L = \lambda T$ and $L_q = \lambda T_q$, where L and L_q represent the number of SSs in the system and queues respectively, to get $T = 1/\mu + T_q = 1/\mu + L_q/\lambda$ and we have

$$T = \frac{1}{\mu} + \frac{r^m}{m!(m\mu)(1-\rho)^2}\left(\frac{r^m}{m!(1-\rho)} + \sum_{n=0}^{m-1}\frac{r^n}{n!}\right)^{-1}. \quad (1)$$

A. Delay Estimation of Legacy IEEE 802.16

The IP lookup processing server can be modeled as an $M/M/1$ model, since the output of an $M/M/m$ queue is identical to its input [4]. Assume the length of each packet in the request of an SS is an exponential distribution with a mean length ℓ. Let $h = k/\ell\mu$ be the number of packets in a request, then the mean number of packets arrival rate to the IP lookup will be $\lambda' = k\lambda/\ell\mu$. Let μ' denote the mean service rate of the IP lookup process (the number of packets per frame). We let $\rho' = \lambda'/\mu'$ be the IP lookup server queues, where ρ' is the traffic utilization. Then the IP lookup delay time T' is equal to $L'/\lambda' = L\ell\mu/k\lambda = \ell\mu\rho'/k\lambda(1-\rho') = \ell\mu/(\ell\mu\mu' - k\lambda)$, where $L' = \rho'/(1-\rho')$. From (1) and T', we get the IP lookup system processing delay of the legacy IEEE 802.16 $T_{802.16} = T + T' + T$ and is equal to

$$T_{802.16} = \frac{\ell\mu^2 + 2\ell\mu\mu' - 2k\lambda}{\ell\mu^2\mu' - k\lambda\mu} + \frac{\frac{2r^m}{m!(m\mu)(1-\rho)^2}}{\left(\frac{r^m}{m!(1-\rho)} + \sum_{n=0}^{m-1}\frac{r^n}{n!}\right)}. \quad (2)$$

B. Delay Estimation of CCSM

The CCSM only needs to take one packet of a request (the same source-destination pair) every time for IP lookup since it will build up a label switching table in the MAC layer for fast cut-through usage. Notice that each request comprises several packets. The input traffic to the IP lookup process is the same as the average arrival rate λ to the MAC layer. Then, the traffic utilization of CCSM to IP lookup could be $\rho'' = \lambda/\mu'$. Therefore, the IP lookup processing delay T'' can be obtained from $L''/\lambda = \rho''/\lambda(1-\rho'') = 1/\mu' - \lambda$, where $L'' = \rho''/(1-\rho'')$. The system processing delay time of CCSM $T_{\text{CCSM}} = T + T''$ will be

$$T_{\text{CCSM}} = \frac{\mu + \mu' - \lambda}{\mu\mu' - \lambda\mu} + \frac{\frac{r^m}{m!(m\mu)(1-\rho)^2}}{\left(\frac{r^m}{m!(1-\rho)} + \sum_{n=0}^{m-1}\frac{r^n}{n!}\right)}. \quad (3)$$

IV. Simulation and Numerical Results

To compare the performance of CCSM with the legacy 802.16 mechanism, we adopt the NCTUns simulation tool for practical IP lookup processing simulations [5]. The simulation is used to validate the numerical results obtained from $T_{802.16}$ (2) and T_{CCSM} (3). The simulation environment is built up by one BS with a variable number of SSs sharing one 10 MHz bandwidth channel, which is operating in an orthogonal frequency division multiple access (OFDMA) PHY mode with a size of 1024 fast fourier transform (FFT) and the time division duplex (TDD) mode. Each OFDMA frame length is 5 ms long and the ratio of downlink to uplink is 2:1. According to the standard, in the uplink, there are 35 subchannels in one channel and each of them has 24 data symbols. Each MAC-slot (in slot for short) is composed of three OFDMA symbols. Therefore, the capacity of the uplink $C = 35 \times 24/3 = 280$ slots. The modulation and coding scheme is 16-QAM with 1/2 coding rate and each slot will carry 33.5 bytes.

First we compare the access delay of the legacy IEEE 802.16 and that of CCSM. The average number of SSs arrival rate is $0 \leq \lambda < 2$ throughout all the simulations. The required bandwidth of each request in each frame from SSs follows the exponential distribution with a mean length $N_s = k/\mu$. In the steady state condition $\rho < 1$, i.e., $\lambda < m\mu = 2$, we compare the average access delay of packets from SSs under different packet sizes $\ell = 2, 4, 11, 22$ slots. Assume two subchannels are reserved for initial ranging and bandwidth contention usage, and the allowed bandwidth for each request is $k = 24$ (this parameter is based on QoS policy). Then only 264 slots are available for data transmission and the maximum number of SSs in the system (servers) is $m = 264/k = 11$.

The simulation results (the dotted lines) and the numerical results (the solid lines) are shown in Fig. 2. It shows that the simulation results match the numerical results in each case. The gap between the curves of simulation and analysis is caused by the frame processing delay (one frame duration 5 ms) in the MAC layer of NCTUns when ρ is low. The results show that CCSM outperforms the legacy IEEE 802.16 in access delay when ρ increases. $T_{802.16}$ increases because of the delay caused by IP lookup (assume each packet needs 1 ms for IP looking up [6]). The IP lookup process in legacy 802.16 will be prolonged when $\rho = 0.035, 0.07, 0.2, 0.4$ ($\ell = 2, 4, 11, 22$), because each packet has to process the IP lookup. Therefore, the more packets there are (smaller ℓ), the sooner $T_{802.16}$ will

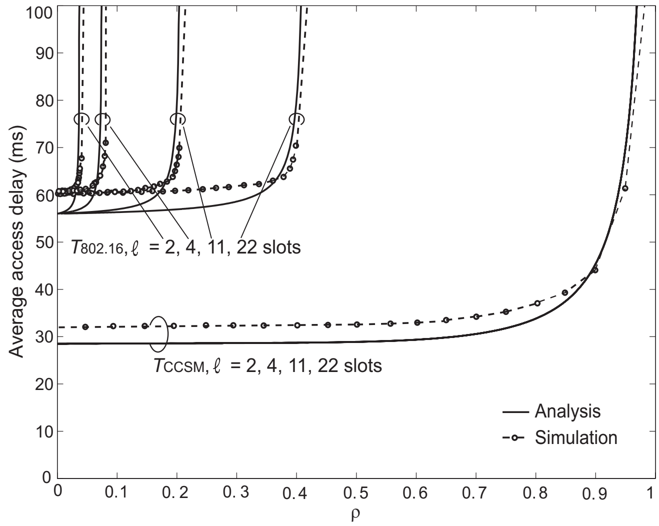

Fig. 2. Average access delay vs. ρ when $N_s = 132$, $\mu = 1/5.5$, $m = 11$, and $k = 24$ under different $\ell = 2, 4, 11, 22$ slots.

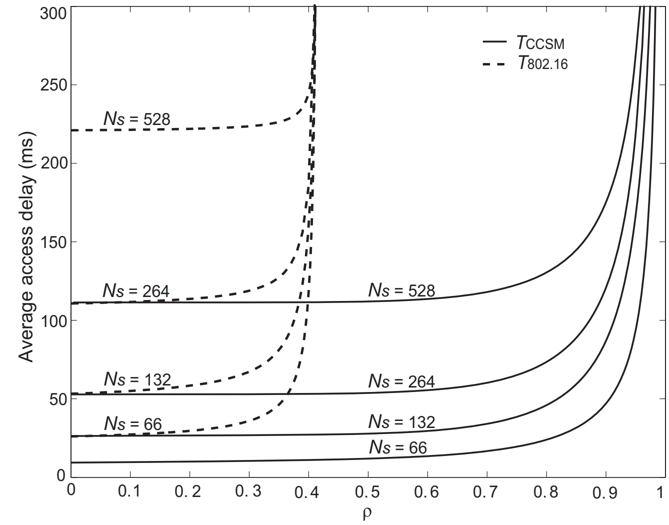

Fig. 3. Average access delay vs. ρ when $m = 11$, $k = 24$, and $\ell = 22$ under different transmission lengths $N_s = 66$, 132, 264, and 528 slots.

TABLE I
SIMULATION PARAMETERS IN IEEE 802.16D/E AND CCSM

Parameter	Value			
N_s	66	132	264	528
μ	1/2.75	1/5.5	1/11	1/22
λ	0–4	0–2	0–1	0–0.5

reach infinity. On the other hand, CCSM will not be confined by the number of packets (different ℓ) because the streaming data will target to the same destination and look up IP once and then it will be switched in the MAC layer. Obviously, as shown in Fig. 2, $T_{802.16}$ is twice as long as T_{CCSM} in each case. CCSM is suitable for the real computer networks since the statistical average packet size is only about 50–150 bytes ($\ell = 2$ to 4) long [7], while the legacy 802.16 suffers a longer delay for IP lookup.

It is an interesting observation on the access delay between $T_{802.16}$ and T_{CCSM} as N_s increases in size. Fig. 3 illustrates the influence of different $N_s = 66, 132, 264, 528$ per request on $T_{802.16}$ and T_{CCSM} (528 slots/frame $\approx$ 28.4 Mbits/sec) when ρ increases. The detailed corresponding parameters are shown in Table I. First, as shown in the figure, both $T_{802.16}$ and T_{CCSM} increase as ρ increases. There is no doubt that when ρ is high, congestion could happen in both the legacy routing mechanism (IEEE 802.16) and the proposed CCSM. However, CCSM can achieve higher performance than legacy IEEE 802.16 can do not only in average access delay (the half access delay of IEEE 802.16 in each case) but also in heavy traffic condition that is CCSM can remain a stable T_{CCSM} until $\rho \approx 0.8$, while $T_{802.16}$ approaches infinite when $\rho \approx 0.4$. This is because CCSM uses a simple yet powerful mechanism to enable the router to identify the first packet in a flow and then just prescreen the remaining packets and bypass the routing and queueing stages. This mechanism especially fit the flow-based IEEE 802.16 protocol because the mechanism use a cross-layer and a label switching approach in MAC layer to efficiently shorten the IP lookup processing time. Results also show that CCSM can efficiently process most frequently used data streaming transmission activities in modern computer networks.

V. CONCLUSIONS

The IEEE 802.16 BS plays an important role as a gateway to Internet or Intranet for SSs. To solve the problem of the congestion and delay of data transmission, we propose a cross-layer (layer 2 and layer 3) switching mechanism named CCSM by studying its performance and comparing to the legacy IEEE 802.16 protocol under different conditions. This approach would boost throughput, reduce packet loss and delays, allow new capabilities like fairness controls and, what's better, it would save power, size, and cost. Simulation results show that CCSM outperforms the legacy IEEE 802.16 either in small or large packet sizes or even in huge multimedia streaming conditions. What is more, this mechanism can also be further extended to WiMAX networks and be used to connect multi-protocol label switching (MPLS) backbone networks.

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