

Performance Analysis of WiMedia UWB System with Wireless Video Traffic

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Abstract—Using Markov chain model we propose a queueing model to analyze the performance of WiMedia system with frame aggregation of video traffic. Then we propose an analytic method to find the solution of the queueing model. To validate the proposed method, we compare the simulation result and the analytic solution in the average throughput, the mean delay, and the frame loss rate.

Index Terms—Performance analysis, UWB, Gigabit, Wireless, Video.

I. INTRODUCTION

Ultra-wideband (UWB) technology offers very large bandwidth of more than a few hundreds Mbytes. Also UWB technology consumes very low power. Because of the features, many new UWB technology areas have been developed. A WiMedia technology is the most dominant one among the UWB technology areas. The WiMedia physical layer (PHY) guarantees 1 Gbps bandwidth [2]. Despite the high speed of WiMedia PHY, the average application bandwidth of WiMedia-based products are below 100 Mbps. Because of the high speed rate, the main applications of a WiMedia technology are video applications, such as high-definition personal video recorder, Internet protocol television and wireless video area networks.

In this paper, we consider a WiMedia system which consists of multiple devices that share a wireless channel to transmit video traffic. To support video traffic, we need to use a hard distributed reservation protocol [3] since a high speed transmission is required for real time traffic. Also, we need to use a row reservation scheme [3] since video traffic needs periodic channel allocations for low transmission delay.

In a WiMedia system, to decrease the transmission overhead, aggregation of multiple video frames into a single data frame is required. Since the transmission channel is not perfect, an error can occur during the transmission. As the aggregation size increases, the transmission overhead decreases while the transmission error rate increases. It is very important to analyze the frame aggregation effect on the performance of a WiMedia system.

Many researches have studied the performance of the WiMedia system [4]–[8]. To the best of our knowl-

edge, however, the frame aggregation effect in the WiMedia performance was considered only in [8]. In [8], the Poisson arrival process was used for modelling input traffic. However, the Poisson arrival process is not appropriate for video traffic since video traffic is burst.

In this paper, using Markov chain model we propose a queueing model to analyze the performance of WiMedia system with the frame aggregation and the transmission error. To account for the burstiness of video traffic, we use the two-state Markov modulated Bernoulli processes (MMBP) model. Then we propose an analytic method to find the solution of the queueing model. Using simulation, we validate the proposed method. We compare the simulation result and the analytic solution in the average throughput, the mean delay, and the frame loss rate.

II. SYSTEM DESCRIPTION

The WiMedia system consists of N devices. Each device shares a radio frequency channel in a time division multiple access (TDMA) manner. There is no hierarchy or master-slave relation among devices. Each device can negotiate its desired transmission time slot with other devices.

In WiMedia media access control (MAC), the channel transmission time is divided into superframes. Each superframe is composed of 256 MAC access slots (MASs) where each MAS is 256 μ s in duration [3]. In addition, a beacon period is defined within a superframe. A beacon period is a set of beacon slots where each beacon slot is 85 μ s long. A beacon period overlays on top of MASs at the beginning of a superframe [3].

Using the beacon slot, each device transmits a beacon frame to share network information and to negotiate and announce MAS reservations with other devices. MAS that falls outside of the beacon period is used for data transmission.

WiMedia MAC uses a distributed reservation protocol (DRP) for the MAS reservation. Using the beacon frame, a reservation owner (a device intending to transmit) sends a request to a reservation target (a device that is to receive the transmission). If the target device accepts the request, the reservation is granted.

The DRP has five reservation types. In this paper, we consider a hard DRP type which the reserved MASs are exclusively used by the owner and the target. The hard type is suitable for video traffic since a high speed transmission is required for the video traffic to provide quality-of-service (QoS).

The 256 MASs of a superframe are represented by a 16×16 matrix, $M = (m_{i,j})$. In a superframe, the order of MASs is $m_{0,0}, m_{1,0}, m_{2,0}, \dots, m_{13,15}, m_{14,15}, m_{15,15}$. The j -th column is called the zone j in WiMedia MAC. According to applications, a row reservation or a column reservation can be used. In the row reservation, all MASs in the i -th row are reserved for a device. In the column reservation, some consecutive MASs in the j -th column are reserved for a device. In this paper, we suppose the row reservation is used. The row reservation is desired for video traffic since it requires periodic channel allocations for short transmission delays.

To account for the burstiness of video traffic, we use the two-state Markov modulated Bernoulli processes (MMBP) model. The two-state MMBP traffic is represented by the transition diagram of a two-state Markov model as shown in Fig. 1. A frame is generated with probability λ_i when the underlying Markov chain is in state i . The length of the frame is fixed and represented by X . In Fig. 1, α is the transition probability from state 1 to state 2 and β is the transition probability from state 2 to state 1. The MMBP model allows the modelling of burst video traffic while keeping the analytical solution of related queueing system tractable.

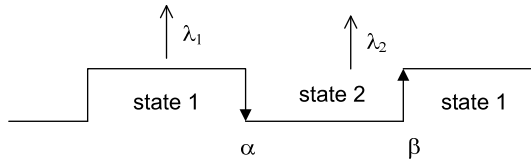


Fig. 1. MMBP traffic model

To transmit a video frame, physical layer convergence protocol (PLCP) preamble and PLCP header are required. When a target device receives a video frame from an owner device, the target device sends an acknowledgement frame to the owner device. An inter-frame space is used to separate the video frame and the acknowledgement frame. The PLCP preamble, the PLCP header, the inter-frame space and the acknowledgement frame are the overhead. By the way, the transmission rate of the PLCP preamble and the inter-frame space is fixed and independent from the data transmission rate [3]. The overhead severely affects the transmission efficiency when the data transmission rate is high. To improve the transmission efficiency, aggregation of multiple video frames into a

single larger data frame is required.

Since the transmission channel is not perfect, an error can occur during the transmission. When a transmission error occurs, a target device notifies the error to an owner device using the acknowledgement frame. The owner device retransmits the data frame that were received incorrectly by the target device. In this paper, we assume that the transmission error rate of a video frame is r , $0 < r < 1$. When multiple video frames are aggregated into a single frame, the transmission error rate of the aggregated frame is proportional to the number of the video frames. If m is the number of video frames in an aggregated frame, mr is the transmission error rate of the aggregated frame.

III. QUEUEING MODEL

Since Ethernet is widely used in the access networks, we assume that the video traffic is transported to the owner device through Ethernet. The maximum size of the Ethernet data frame is 1500 bytes. In this paper, we assume that the length of a video frame, X , is 1332 bytes by considering the Ethernet header and the video signal characteristic.

Suppose that the time axis is slotted and the length of the time slot is $128 \mu s$. Hence a MAS consists of 2 slots. For simplicity, we suppose that at most one frame can arrive at an owner device per slot. The maximum input bandwidth of a device is $1332 \text{ bytes} / 128 \mu s = 83.25 \text{ Mbps}$. Currently, the most common speed of Ethernet is 100 Mbps in home applications. By considering the extra overhead such as the Ethernet preamble and the Ethernet inter-frame gap, our assumption suffices for the modelling of 100 Mbps Ethernet. In case the input bandwidth is higher than 100 Mbps, the number of slots in a MAS can be increased for the analysis. For simplicity, we only consider when the number of slots is 2 in this paper.

In this paper, we assume the data rate at PHY level is 1024 Gbps, which is equivalent to 1920 bits per 6 symbols where a symbol is 312.5 ns. We need 148 symbols to transmit the overhead that consists of the PLCP preamble, the PLCP header, the inter-frame space and the acknowledgement frame [2], [3]. Since the time slot is 409.6 symbols long, we can use 261.6 symbols for the transmission of video frames. Hence, the maximum value of m is 7. The owner device maintains a finite queue for each target device. The size of the queue is L . A newly arrived frame is discarded when the queue is full.

In this paper, we use the hard DRP reservation type and the row MAS reservation. Hence the owner device reserves consecutive multiple slots for a target device. In addition, we can analyze the given reservation system using a queueing model with the server vacation. The server represents the service of the owner device

for the target device in the queueing model. Because of the row MAS reservation, the service pattern for the target device is repeated in every 32 slots. We assume that the server is in service during a slots and on vacation during $32 - a$ slots for the target device. Fig. 2 shows the service pattern of the server for the target device.

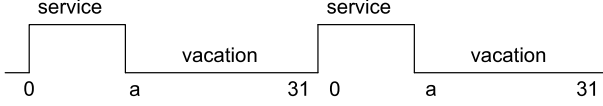


Fig. 2. Service pattern of an owner device for a target device

When the server is in the service mode for a target device, the server can serve up to m video frames at the end of a slot depending on the number of video frames saved in a queue. If the number of video frames in a queue is less than or equal to m , the server can serve all video frames in the queue. If the number of video frames in a queue is greater than m , the server can serve only m video frames. If the transmission error occurs on any of video frames, none of the video frames can be served. Hence the server serves m video frames with probability $1 - mr$.

The traffic arrival follows the MMBP traffic model which we mentioned before. We assume that a video frame arrives at the beginning of a slot. In addition, we suppose that the video frame arrived at the beginning of a slot cannot be served at the end of the same slot since a frame needs a processing time to be saved in a queue in a real world.

IV. ANALYSIS

In this section, we model the WiMedia system using the discrete time Markov chain queueing model. Then we analyze the queueing model. Let $s(b, i, k, t) = Pr\{c(t) = b, n(t) = i, e(t) = k\}$. The variable $c(t)$ is the state of the two-state MMBP model at the slot t , $b = 1, 2$ mean the states 1 and 2 of the two-state MMBP model, respectively. The variable $n(t)$ is the queue length at the slot t where $0 \leq n(t) \leq L$. The variable $e(t)$ is the server service state at the slot t where $0 \leq e(t) \leq 31$. The variable $e(t)$ increases by 1 in every slot and $e(t)$ becomes 0 after it reaches to 31. If $0 \leq e(t) \leq a - 1$ then the server is in the service mode while if $a \leq e(t) \leq 31$ then the server is on the vacation mode.

Let $s(b, i, k) = \lim_{t \rightarrow \infty} s(b, i, k, t)$. In the steady state, we have $s(b, i, k, t + 1) = s(b, i, k, t) = s(b, i, k)$. For $m \leq i \leq L - 8$, we obtain the state transition equation of the WiMedia system in the steady state as

$$\begin{aligned} s(1, i, 0) &= s(2, i - 1, 31)\beta\lambda_2 + s(2, i, 31)\beta(1 - \lambda_2) \\ &\quad + s(1, i - 1, 31)(1 - \alpha)\lambda_1 \\ &\quad + s(1, i, 31)(1 - \alpha)(1 - \lambda_1). \end{aligned} \quad (1)$$

For $m \leq i \leq L - 8$ and $1 \leq k \leq a$, we have

$$\begin{aligned} s(1, i, k) &= s(2, i + m, k - 1)\beta(1 - \lambda_2)(1 - mr) \\ &\quad + s(2, i + m - 1, k - 1)\beta\lambda_2(1 - mr) \\ &\quad + s(2, i, k - 1)\beta(1 - \lambda_2)mr \\ &\quad + s(2, i - 1, k - 1)\beta\lambda_2mr \\ &\quad + s(1, i + m, k - 1)(1 - \alpha)(1 - \lambda_1)(1 - mr) \\ &\quad + s(1, i + m - 1, k - 1)(1 - \alpha)\lambda_1(1 - mr) \\ &\quad + s(1, i, k - 1)(1 - \alpha)(1 - \lambda_1)mr \\ &\quad + s(1, i - 1, k - 1)(1 - \alpha)\lambda_1mr. \end{aligned} \quad (2)$$

For $m \leq i \leq L - 8$ and $a + 1 \leq k \leq 31$, we get

$$\begin{aligned} s(1, i, k) &= s(2, i - 1, k - 1)\beta\lambda_2 + s(2, i, k - 1)\beta(1 - \lambda_2) \\ &\quad + s(1, i - 1, k - 1)(1 - \alpha)\lambda_1 \\ &\quad + s(1, i, k - 1)(1 - \alpha)(1 - \lambda_1). \end{aligned} \quad (3)$$

For $m \leq i \leq L - 8$, we obtain

$$\begin{aligned} s(2, i, 0) &= s(2, i - 1, 31)(1 - \beta)\lambda_2 \\ &\quad + s(2, i, 31)(1 - \beta)(1 - \lambda_2) \\ &\quad + s(1, i - 1, 31)\alpha\lambda_1 + s(1, i, 31)\alpha(1 - \lambda_1). \end{aligned} \quad (4)$$

For $m \leq i \leq L - 8$ and $1 \leq k \leq a$, we have

$$\begin{aligned} s(2, i, k) &= s(2, i + m, k - 1)(1 - \beta)(1 - \lambda_2)(1 - mr) \\ &\quad + s(2, i + m - 1, k - 1)(1 - \beta)\lambda_2(1 - mr) \\ &\quad + s(2, i, k - 1)(1 - \beta)(1 - \lambda_2)mr \\ &\quad + s(2, i - 1, k - 1)(1 - \beta)\lambda_2mr \\ &\quad + s(1, i + m, k - 1)\alpha(1 - \lambda_1)(1 - mr) \\ &\quad + s(1, i + m - 1, k - 1)\alpha\lambda_1(1 - mr) \\ &\quad + s(1, i, k - 1)\alpha(1 - \lambda_1)mr \\ &\quad + s(1, i - 1, k - 1)\alpha\lambda_1mr. \end{aligned} \quad (5)$$

For $m \leq i \leq L - 8$ and $a + 1 \leq k \leq 31$, we get

$$\begin{aligned} s(2, i, k) &= s(2, i - 1, k - 1)(1 - \beta)\lambda_2 \\ &\quad + s(2, i, k - 1)(1 - \beta)(1 - \lambda_2) \\ &\quad + s(1, i - 1, k - 1)\alpha\lambda_1 \\ &\quad + s(1, i, k - 1)\alpha(1 - \lambda_1). \end{aligned} \quad (6)$$

We omit the state transition equations in the steady state for $0 \leq i < m$ and $L - 8 < i \leq L$ since it can be obtained similar to Eqs. (1)-(6).

To solve the state transition equations in the steady state, define $64(L + 1) \times 1$ matrix, S as

$$S = [s(1, 0, 0), s(1, 0, 1), \dots, s(2, L, 30), s(2, L, 31)]^T$$

Also, define $64(L + 1) \times 64(L + 1)$ matrix A as

$$A = (a_{uv}).$$

The element a_{uv} is a state transition probability from the state $s(b_1, i_1, k_1)$ to the state $s(b_2, i_2, k_2)$ where $u = 64i_1 + 32(b_1 - 1) + k_1$ and $v = 64i_2 + 32(b_2 - 1) + k_2$.

Then we can write the state transition equations in the steady state as

$$S = AS. \quad (7)$$

We can write Eq. (7) as

$$AS = \lambda S, \quad \lambda = 1. \quad (8)$$

The solution of Eq. (7) is the eigen vector S of Eq. (8) when the eigen value $\lambda = 1$. In this paper, in order to get the eigen vector S , we apply the power iteration method. We solve the following iterative equation with the initial value of $S(0)$ using the power iteration method.

$$S(k+1) = \frac{AS(k)}{\|AS(k)\|}. \quad (9)$$

Since $\|AS(k)\| = 1$ in the given state transition equation, we have $S(k+1) = AS(k)$.

The fraction of the first eigen value and the second eigen value determines the convergence speed of the power iteration method. If the fraction is close to 1, the convergence speed becomes extremely slow. To increase the convergence speed, we modify the iterative equation as

$$(1 - \sigma)S(k+1) = (A - \sigma I)S(k) \quad (10)$$

where σ is a constant and changes the fraction. When we get the solution S , the average throughput is obtained as

$$TH = \sum_{b=1}^2 \sum_{i=1}^m \sum_{j=0}^{a-1} s(b, i, j) i (1 - ir) + \sum_{b=1}^2 \sum_{i=m+1}^L \sum_{j=0}^{a-1} s(b, i, j) m (1 - mr).$$

The mean buffer length is given by

$$ML = \sum_{b=1}^2 \sum_{i=1}^L \sum_{j=0}^{31} s(b, i, j) i.$$

Also, by the Little's law, the mean delay is

$$MD = \frac{ML}{TH}.$$

Finally, the frame loss rate is obtained as

$$LR = \sum_{b=1}^2 \sum_{j=0}^{31} s(b, L, j).$$

V. PERFORMANCE EVALUATION

In this section, we validate the proposed analysis method using simulations. We consider a system where the maximum number of video frames in an aggregated frame is $m = 7$, the maximum buffer level is $L = 1000$, the retransmission rate of a video frame is $r = 0.002$, and the number of service slots is $a = 4$. The traffic parameters are $\alpha = 0.5$, $\beta = 0.5$, and $\lambda_2 = 0.9$.

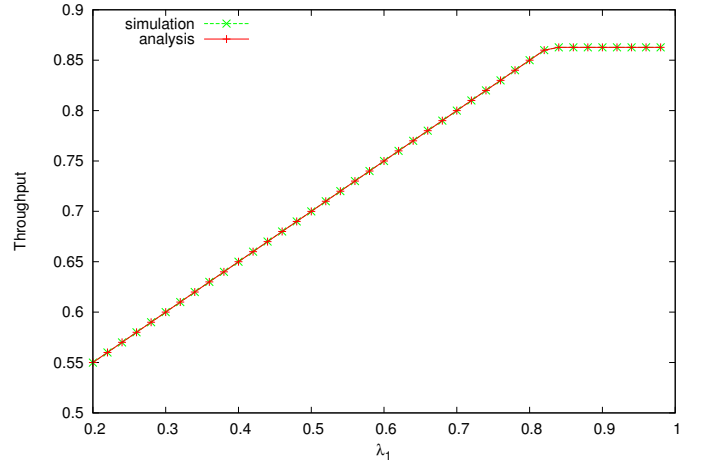


Fig. 3. Average throughput comparison

Increasing λ_1 from 0.2 to 0.98, we compare the results of the proposed method with those of the simulation. In the analysis, we use $\sigma = -0.5$ and the initial value of $S(0) = [0, 0, \dots, 0, 1]^T$. Simulation is performed until the total number of frames transmitted exceeds 10^8 for each plot point.

Figs. 3-5 show the results of proposed method are almost same to those of simulation. Since the number

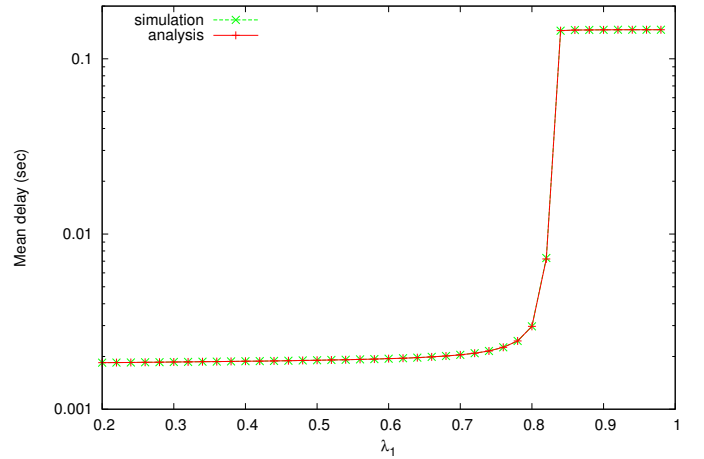


Fig. 4. Mean delay comparison

of active slots is $a = 4$ and the maximum number of aggregated frames is $m = 7$, the maximum achievable throughput is $4 \times 7 \times 1332 \times 8 \times (32 \times 128 \mu s) = 72.84$ Mbps. In Fig. 3, the saturated throughput rate is about 87%. Since the maximum input bandwidth is 83.25 Mbps as we mentioned before, the maximum throughput is about $0.87 \times 83.25 = 72.4$ Mbps. This result shows the proposed method and the simulation are valid.

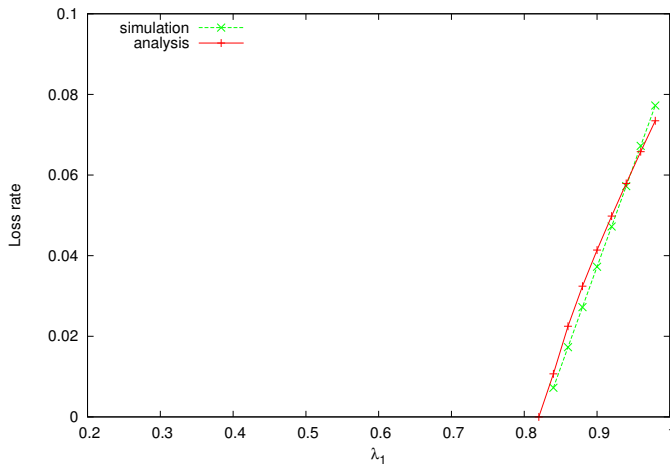


Fig. 5. Frame loss rate comparison

VI. CONCLUSIONS

We proposed a queueing model for the analysis of performance of WiMedia system with the frame aggregation and the frame re-transmission due to a transmission error. To account for the burstiness of video traffic, we used the two-state MMBP model. We proposed an analytic method by applying the power iteration method to find the steady-state solution of the queueing model. Using simulation, we validate the proposed method. We compare the simulation result and the analytic solution in the average throughput, the mean delay, and the frame loss rate.

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