DYNAMIC RATE SELECTION (DRS) SCHEME FOR UWB SYSTEMS SUPPORTING VIDEO MULTICAST SERVICES

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ABSTRACT

This paper presents a dynamic rate selection (DRS) scheme to determine the transmission rate of video multicast services for ultra-wideband (UWB) systems. The DRS scheme utilizes the received signal quality of the beacon frame sent by each UWB device to estimate clients’ location distribution. It then determines the best data rate to transmit the enhancement layer portion of the multicast video stream. Considering the limited processing power of the USB device, a decision tree is further proposed to reduce the computational complexity of the DRS. The performance of the DRS scheme is verified via computer simulation. Simulation results demonstrate the effectiveness of the proposed DRS scheme in various conditions.

Key Words: ultra-wideband (UWB), video multicast services, dynamic rate selection.

I. INTRODUCTION

One of the important building blocks in an intelligent building is the consumer network. A consumer network is a wireless network consisting of multiple consumer devices. Each consumer device is normally equipped with a display and a wireless network interface. These consumer devices enrich our daily life via offering smart features including various kinds of multimedia services. Fig. 1 shows the concept of a consumer network. In this network, consumer devices such as cellular phones, personal computers (PCs), personal digital assistants (PDAs), video cassette recorders (VCRs), wireless audio video (AV) systems, and liquid crystal display (LCD) televisions are interconnected via one or more wireless technologies such as WiFi, Zigbee, Bluetooth, infrared data association (IrDA), and ultra-wideband (UWB). Among them, UWB is one of the most promising and widely addressed techniques for in-home communication (Chung et al., 2005).

The industry’s first UWB standard has been developed based on WiMedia UWB. WiMedia UWB aims to support short-range multimedia file transfers at data rates of 480 Mbit/s and beyond with low power consumption. The operating frequencies of WiMedia UWB range from 3.1 to 10.6 GHz. The frequency band is divided into 14 bands and each of them has a bandwidth of 528 MHz (Blazevic et al., 2004). The WiMedia UWB uses multiband-orthogonal frequency division modulation (MB-OFDM) to combat the multipath fading effect in indoor environments. It supports data rates ranging from 53.3 to 480 Mb/s. In WiMedia UWB, there is no access point or central coordinator. Each device shall transmit a beacon frame in the beacon period to indicate its basic timing, device recovery, resource reservation, and scheduling information. The device shall also listen to the beacon frames sent by the other devices to receive data and determine its own scheduling information.

The maximum attainable data rate between two USB devices is specified in terms of the minimum receiver sensitivity (ECMA International, 2008) (Batra et al., 2004). The sensitivity requirement is determined based on link-level simulation results for a specific frequency band in additive white Gaussian noise (AWGN) or multi-path channel environments (Batra et al., 2004). Normally, a higher data rate requires a higher sensitivity number in order to attain the same target packet error rate and link success probability. However, the sensitivity numbers are subject to variations in noise figure over process,
The wireless connectivity capability and the multimedia processing power of the consumer devices offer us a chance to create a wide variety of new multimedia services. Among these services, video multicast service is the most promising service to be supported in in-home environments. In video multicast services, we need a multimedia server (also known as a media center) to deliver multimedia content (e.g., text, audio, picture, video) to consumer devices. Scalable video coding (SVC) is a technique that encodes a video stream once at highest resolution and the receiver may decode from partial streams depending on the specific rate (Ohm, 2005). With SVC, the receiver may reconstruct low resolution or low quality video from incomplete bit streams. It is a very useful feature for supporting video multicast services under dynamically changing network environments. One of the approaches for SVC is to encode a video stream into one base layer (BL) and multiple enhancement layers (ELs) (Servetto et al., 2000). In this approach, an EL sub-stream is successfully decoded if and only if the BL and all of the lower EL sub-streams are correctly decoded. Denote the nth enhancement layer as $EL_n$. $EL_m$ will be discarded if either BL or any of $EL_n$ ($n < m$) are lost. The SVC may work with the dynamic rate selection scheme to offer different levels of quality of service (QoS) for clients. For example, the minimum data rate can be used to transmit BL to guarantee the basic video quality for all clients. A higher data rate may then be used to transmit EL(s) such that clients with better received signal quality may receive more ELs and thus, enjoy a better video quality.

To the best of our knowledge, no dynamic rate selection scheme has been proposed for in-home multicast service. Kuo and Wu (2009) proposed a dynamic resource allocation (DRA) algorithm to reserve radio resources based on an online video-traffic predictor. However, this algorithm method is designed for uni-cast service and its performance is highly dependent on the accuracy of the predictor. Kim and Cho (2005) proposed an adaptive modulation and coding (AMC) scheme to adjust the transmission rate of SVC-based multicast services for cellular systems. The decision is made based on client’s priority and video quality feedback sent by each client. Cheng et al. (2007) proposed a dynamic rate adjustment (DRA) algorithm for WiMAX systems based on the feedback sent by each client.

Most of the existing approaches were developed specifically for wide area networks. Some common assumptions were made in these approaches. First of all, the radio resource is always greater than clients’ demand in such a centralized controlled environment. Second, the computational complexity can be ignored since the base station has enough processing power to handle everything. Third, the base station can reserve dedicated uplink resources for each client to send its feedback. However, most of the aforementioned assumptions are not applicable for UWB-based in-home environments. In such environments, multiple UWB networks are overlapped and they have to share the same radio spectrum in a time-division manner. Hence, the radio resources reserved for multicast service may be limited. Moreover, the dynamic rate selection algorithm needs to be implemented in a network device with limited processing power (e.g., USB dongle). Furthermore, it is not possible for a USB device to reserve dedicated resources for the other USB devices to send their feedback.

In this paper, a dynamic rate selection (DRS) scheme is proposed to determine the transmission rate of BL and ELs of the SVC-based multicast video services for UWB systems. The decision is made according to the estimated number of clients located in each data rate region subject to the constraint of limited transmission time reserved for multicast services. The computational complexity of the proposed DRS scheme is then reduced by utilizing the parameters calculated in the previous decision. The rest of the paper is organized as follows. The system model adopted by this paper is described in Section II. Section III presents the details of the proposed DRS scheme. Simulation results are given in Section IV. Conclusions are finally drawn in Section V.
II. SYSTEM MODEL

The system model of a consumer network adopted in this paper is shown in Fig. 2. The network consists of a multimedia server and multiple multimedia devices which are interconnected by USB technology. The USB dongle is a UWB transceiver directly connected to the multimedia server and is responsible for transmitting the multimedia content to the clients. The transmission range of the USB dongle can be divided into several data rate regions. Let $m_i$ be the $i$th data rate (unit: bits/sec.) supported in UWB; $m_1$ and $m_8$ be the maximum and the minimum data rates, respectively. A data rate region $i$ is a set of geographical locations in which clients can decode data transmitted by the USB dongle using a data rate not less than $m_i$. It can be determined based on a minimum receiver sensitivity requirement of the data rate $m_i$ (ECMA International, 2008). Note that the data regions shown in Fig. 2 are used for the ease of illustration. In home environments, the boundaries of these data rate regions will be irregular.

It is assumed that the multimedia server adopts scalable video coding and encodes the video stream into one BL and one or more ELs. It is also assumed that the BL data is invariably delivered at the minimum data rate to ensure a minimum quality level for all clients. In contrast, the EL data is dynamically transmitted using a data rate determined by a DRS scheme. For the ease of demonstration, only one EL has been considered in this paper. The proposed DRS scheme can be extended to support multiple ELs.

Figure 3 shows the MAC superframe structure of WiMedia UWB. Each superframe consists of 256 media access slots (MASs) = 65,536 µsec. Figure 3 MAC superframe structure of WiMedia UWB

III. DYNAMIC RATE SELECTION SCHEME

In this section, details of the proposed DRS scheme are described. The purpose of the DRS scheme is to adjust the transmission data rate based on clients’ location distribution. As illustrated in Fig. 2, the minimum receiver sensitivity requirement of each data rate divides the coverage area of the USB dongle into several regions. In WiMedia UWB, eight data rates are supported (ECMA International, 2008).

The parameters used in this paper are listed below:

- $m_j$: the $j$th ($1 \leq j \leq 8$) data rate specified in the WiMedia UWB specification, $m_i > m_j$ if $i < j$;
- $B$: the size of the multicast video stream generated during a superframe (unit: bits), in which $\alpha$ portion is encoded as BL and the $(1-\alpha)$ portion is encoded as EL;
Eq. (4) contains two parts, which correspond to the quality index contributed by BL and EL, respectively. The first part can be ignored in the selection of $R$ since it is a constant.

Consider the case that the time constraint in Eq. (4) is removed (i.e., $T_{\text{max}} \to \infty$). In this case, the overall quality index is maximized by choosing the maximum value of $i$ (i.e., $R = m_i$). That is, the USB dongle uses the minimum data rate to transmit EL to all clients. In this case, all clients can decode the EL correctly and thus, $Q$ is maximized. In contrast, a higher data rate is required to compensate the effect of decreased $T_{\text{max}}$. And, there is a tradeoff among $j$, $M_i$, and $m_j$. A higher transmission rate $m_j$ may result in a higher percentage of EL to be received for clients $M_i$ with $i < j$. However, this implies that the clients $M_i$ with $i > j$ will fail to receive the EL, which degrades the overall quality index.

Consider the following cases:

**Case I.** $M_i = 0$ for $i \geq 2$. In this case, all clients are located in data rate region 1 and thus, $R = m_1$.

**Case II.** $M_i = 0$ for $i \geq 3$. In this case, all clients are located in data rate regions 1 and 2. Hence,

$$R = \begin{cases} m_1, & \text{if } Q(1) - Q(2) \geq 0; \\ m_2, & \text{otherwise}. \end{cases}$$

If we combine Eqs. (4) and (5), we can have

$$R = \begin{cases} m_1, & \text{if } \min(m_1) \frac{T_{\text{max}} - \frac{\alpha B}{m_i}}{\frac{\alpha B}{m_i}}, 1 - \alpha \geq \min(m_2) \frac{T_{\text{max}} - \frac{\alpha B}{m_i}}{\frac{\alpha B}{m_i}}, 1 - \alpha; \\ m_2, & \text{otherwise}; \end{cases}$$

where

$$\theta_{2,1} = \left[ \frac{\min(m_1) \frac{T_{\text{max}} - \frac{\alpha B}{m_i}}{\frac{\alpha B}{m_i}}, 1 - \alpha}{\min(m_2) \frac{T_{\text{max}} - \frac{\alpha B}{m_i}}{\frac{\alpha B}{m_i}}, 1 - \alpha} - 1 \right] \times M_i.$$
Combine Eqs. (4) and (8), we can have

\[
R = \begin{cases} 
  m_1, & \text{if } \theta_{2,1} \geq M_2 \text{ and } \theta_{3,1} \geq M_3; \\
  m_2, & \text{if } \theta_{2,1} < M_2 \text{ and } \theta_{3,2} < M_3; \\
  m_3, & \text{otherwise}.
\end{cases}
\]  

(9)

where

\[
\theta_{3,1} = \frac{\min(m_1(\frac{T_{\text{max}}}{B} - \alpha), 1 - \alpha)}{\min(m_3(\frac{T_{\text{max}}}{B} - \alpha), 1 - \alpha)} - 1 \times M_1 - M_2;
\]

(10)

and

\[
\theta_{3,2} = \frac{\min(m_1(\frac{T_{\text{max}}}{B} - \alpha), 1 - \alpha)}{\min(m_3(\frac{T_{\text{max}}}{B} - \alpha), 1 - \alpha)} - 1 \times \sum_{i=1}^{3} M_i.
\]

(11)

The process can be repeated, and thus, we can find the threshold \( \theta_{i,j} \) to choose between data rates \( m_i \) and \( m_j \) (i.e. \( j < i \)). \( \theta_{i,j} \) is given by

\[
\theta_{i,j} = \frac{\min(m_1(\frac{T_{\text{max}}}{B} - \alpha), 1 - \alpha)}{\min(m_3(\frac{T_{\text{max}}}{B} - \alpha), 1 - \alpha)} - 1 \times \sum_{k=1}^{i-1} M_k - \sum_{k=j+1}^{i} M_k.
\]

(12)

The computational complexity of the overall quality index can be further reduced based on the above observations. An important design concept is that the transmission of EL using data rate \( m_j \) is ineffective for clients in data rate region \( i \) if \( j < i \). Hence, the maximum achievable data rate for \( M_i \) clients is \( m_i \). The selection of \( R \) can be simplified by constructing a decision tree based on the thresholds given in Eq. (12). Fig. 4 shows the decision tree of the proposed DRS. The decision tree is composed of lots of states. Each state denotes a rate selection decision. The \( j \)-th row and the \( i \)-th column state refers to the clients located in data rate region \( i \) that are pre-assigned by rate \( m_j \). Note that, there are \( i \) possible states in data rate region \( i \) and each state refers to a possible transmission rate \( m_i \) for \( j \leq i \).

The initial state of the decision tree is located at the left bottom of the tree. The rationale of the decision tree is to start the DRS at data rate region \( i \) where \( M_i \) is greater than zero. The decision is started from the initial state and moved along the path toward 0 Mbps until finding a non-zero \( M_i \). Initially, a maximum transmission rate of \( m_i \) is assigned to these clients. This triggers a transition to the state for the \( (i + 1) \)th data rate region that has been pre-assigned a data rate of \( m_i \). In each state, a decision is made based on the number of clients in that region, \( M_i \), and the decision threshold \( \theta_{i,j} \).

The state transition in the decision tree has some limitations. The clients located in data rate region \( i \) cannot decode the EL data transmitted using data rate \( m_j \) if \( j < i \). Selecting a high data rate to transmit the EL may reduce the total transmission time. However, the price paid for the reduced transmission time is degraded quality for clients located near the cell border. Hence, the DRS can either keep the transmission rate decided by the previous step, or choose the maximum transmission rate that can be supported in this data rate region. A new transmission rate \( m_i \) will be chosen only if the quality gain of \( M_i \) clients is higher than the quality loss of the other \( \sum_{k=1}^{i} M_k \) clients. The condition is fulfilled when the number of clients in this region is larger than the given threshold. Take the clients in data rate region \( 5 \) with assigned transmission rate \( m_3 \) as an example, the DRS will adjust the transmission rate to \( m_5 \) only if \( M_5 > \theta_{5,3} \). Otherwise, the same transmission rate \( m_3 \) will still be used. The process will be repeated until it reaches the final state, which determines the final transmission data rate \( R \).

The operation of the proposed DRS scheme is summarized below. Initially, the USB dongle has to identify the available time \( T_{\text{max}} \) that can be used by the multicast service. The media server then decides the coding rate \( B \) and the BL ratio \( \alpha \) based on \( T_{\text{max}} \). The DRS scheme is executed once during each DRS update period. At the beginning of each DRS update period, the USB dongle shall estimate the number of clients located in each data rate region \( M_i \) (or, clients’ location distribution) and calculate \( \theta_{i,j} \) based on \( B \) and \( \alpha \) according to Eq. (11). At the beginning of the DRS update period, the USB dongle has to
estimate clients’ location distribution. The DRS then selects the transmission rate, \( R \), for EL according to the decision tree shown in Fig. 4 to maximize the overall quality index \( Q \). Finally, the USB dongle will use the selected data rate to transmit the EL data and announce the allocation of its video streams in its beacon frame.

The decision tree offers us a simplified rate selection procedure. However, it does not significantly reduce the overall computational complexity. In order to further reduce the computational complexity, the correlation between two successive DRS decisions needs to be considered. In this paper, \( T_{\text{max}} \) and \( M_i \) are periodically updated by monitoring the information announced by the beacon frames. The DRS update period may be configured as one or more superframes. It is noted that the moving speed of each client in a digital home is quite slow. Hence, the location distribution of clients within one update period may not be dramatically changed. Based on this observation, the USB dongle may reuse most of the parameters obtained in the previous DRS to determine the new transmission rate to further reduce the computational complexity.

A simple example was used here to illustrate the reduction of computational complexity in DRS using the decision tree. Assume that a client moves from data rate region 4 to data rate region 3 and \( B, \alpha \), and \( T_{\text{max}} \) are not changed during this DRS update period. In response, the USB dongle has to re-select the transmission rate to maximize the overall quality index. Fig. 5 shows the number of cells which needs to be updated in the decision tree. In this figure, each cell represents a set of parameters to be calculated. In this example, \( m_i \left( \frac{T_{\text{max}}}{B} - \frac{\alpha}{M_k} \right) \) is not changed; \( M_i \) is modified only for \( i = 3 \) and 4; and, both \( \sum_{k=1}^{i} M_k \) and \( \sum_{k=j+1}^{i} M_k \) are modified only for \( j = 3 \). As a result, it can be found from Eq. (12) that \( \theta_{i,j} \) is modified for \( i = 4 \) and all \( j < i \); and for \( i = 5 \) to 8 and \( j = 3 \). Note that only a constant addition is required to modify the parameters obtained in the previous DRS update period. In contrast, all of the cells need to be updated if the correlation between two successive DRS decisions is ignored. Similar conclusions can be reached for the modification of \( T_{\text{max}}, B \), or \( \alpha \). In these cases, only a scalar multiplication is required to modify the parameters obtained in the previous DRS update period. In this example, the values of \( M_3 \) and \( \sum_{k=1}^{j} M_k \) will be increased by 1 while the values of \( M_3 \) and \( \sum_{k=j+1}^{i} M_k \) will be decreased by 1.

In this example, the number of updated cells is reduced by utilizing the results calculated in the previous DRS decision. Although some parameters need to be updated, this does not imply that the decision should be made after updating all of the parameters. As shown in Fig. 4, the DRS scheme selects only one path from the initial state to reach a final transmission rate \( R \). In order to have a real-time decision, the updating priority will be given to the \( \theta_{i,j} \) that are on the way to the new path. The rest of the parameters can then be updated in the upcoming superframe(s) without affecting the real-time operation requirement. Hence, a quick decision could be made within one superframe.

IV. SIMULATION RESULTS

Simulations were conducted on top of a C-based simulation platform. In the simulation, an indoor environment was investigated. It was assumed that the video multicasting server was located at the center of the house; and 10 mobile clients were scattered through the house. Each client was directly communicating with a USB dongle connecting video multicasting server, which resulted in a star topology. The moving speed of each client was assumed to be uniformly distributed between 0.5 to 1.5 m/s. A random way point mobility model with 8 directions was used (Giancola et al., 2004). For the ease of demonstration, the maximum transmission time reserved for multicast service \( T_{\text{max}} \) was assumed to be a constant during the simulation. A constant bit rate video encoder with data rate 10 Mbps (i.e., \( B = 655350 \) bits) and BL ratio \( \alpha = 0.7 \) were assumed. Due to the lack of link-level simulation results for all of the eight data rates supported in WiMedia UWB, only an AWGN wireless channel was considered in the simulations. Table 1 lists the data rate \( j \), \( m_j \), and its corresponding sensitivity numbers for WiMedia UWB Band Group 1 in an AWGN wireless channel. The table was obtained by assuming an average transmission power of -9.9 dBm, operation frequency of 3882 MHz, a path loss decay exponent of 2, a noise figure of 6.6 dB, an implementation loss of 2.5 dB, and a margin of 3 dB (ECMA International, 2008).

Three scenarios were investigated. An average quality index, which is the overall quality index
normalized by the total number of clients, was chosen as the main performance metric. The purpose of Scenario I was to investigate the performance of the DRS scheme for a multicast video streaming service of 120 minutes with 10000 samples. The performance of DRS was compared with those using a fixed data rate. Scenario II aimed to evaluate the computational complexity of the DRS scheme. One to ten moving clients were investigated. $T_{\text{max}}$ were set to be 37, 44, and 51 MASs to demonstrate heavy, medium, and light load situations. In Scenario III, the impact of the DRS update period to the computational complexity was studied. Update periods ranging from 1 to 13 superframes were investigated.

1. Scenario I

Figure 6 presents the average quality index achieved by DRS and fixed data rates. $T_{\text{max}}$ was set to be 37 MASs in the simulation. It was found that the DRS scheme always achieved the highest average quality index compared to the fixed data rate cases. Note that, the average quality index was changed due to the moving of clients. However, the average quality index was always no less than $\alpha$ during the simulation, which ensures the minimum video quality received by each of the clients.

2. Scenario II

For the video encoder considered in the simulation, the USB dongle needed 33.62 MASs to transmit the BL part of the video stream in each frame if the transmission rate of 53.3 Mbps was used. One may need 48.03 MASs to transmit both BL and EL parts of the video stream in each frame using 53.3 Mbps. Note that the available time reserved for broadcasting video service was determined based on the availability of the other clients. Therefore, $T_{\text{max}}$ may decrease as traffic loading in the UWB network increases. Hence, three different values of $T_{\text{max}}$ (i.e., 37, 44, 51 MASs) were used to illustrate heavy-load, medium-load, and light-load situations.

Figure 7 shows performance of DRS with and without reduced computational complexity. The number of updated cells was chosen as a performance metric for the ease of demonstration. As mentioned in the last two paragraphs in Sec. III, only part of the parameters in the cell need to be updated. Hence, the performance metric can be used as the worst case analysis for the DRS with reduced computational complexity. It was found in Fig. 7 that an increased number of clients resulted in more computation. It was also found that the computational complexity of both approaches was decreased as $T_{\text{max}}$ increased. Note that some of the $\theta_{i,j}$ will become zero or negative if $T_{\text{max}}$ is large enough to transmit entire EL packets at maximum $R$. In such a case, we don’t have to update $\theta_{i,j}$ anymore since $M_i$ is always no less than zero. Generally speaking, less $\theta_{i,j}$ was updated when a higher $T_{\text{max}}$ was applied.

3. Scenario III

Figure 8 shows the number of update cells for various observation intervals. In this simulation, $T_{\text{max}}$ was set to be 37 MASs. It was found that more clients resulted in a higher computational complexity. This is because the location distribution of clients will change more frequently if more clients are being served. It was also found that a shorter DRS update period resulted in a higher computational complexity. It is because the parameters in the decision tree were normally updated at each observation interval. Hence, the increase of the observation interval may reduce the frequency for updating the parameters. However, the reduction in computational complexity was not noticeable for two clients as opposed to ten clients.

V. CONCLUSIONS

This paper presents a dynamic rate selection (DRS) scheme for delivering multicast services in a consumer network adopting UWB technology. The
DRS scheme adjusts the data rate based on clients’ location distribution. In this paper, we first proposed a decision-tree approach to simplify the rate selection procedure. The computation complexity of the DRS is then further reduced by utilizing the correlation between successive DRS decisions. Simulation results demonstrated the effectiveness of the proposed scheme in various conditions. It was shown that the DRS scheme can always achieve the maximum transmission rate with an acceptable computational complexity.

ACKNOWLEDGMENTS

This study is supported in part by National Science Council, Taiwan, under contract No. NSC 98-2219-E011-005 and conducted under the “Wireless Broadband Communications Technology and Application Project” of the Institute for Information Industry which is subsidized by the Ministry of Economy Affairs of the Republic of China.

NOMENCLATURE

- $B$: the size of the multicast video stream generated during a superframe
- $M_i$: the number of clients located in data rate region $i$
- $m_j$: the $j$th data rate specified in the WiMedia UWB specification
- $Q$: the overall quality index to be maximized
- $R$: the maximum transmission rate used to transmit the enhancement layer portion of the multicast video stream
- $T_{\text{max}}$: the maximum available time reserved for the multicast service
- $\alpha$: the portion encoded as base layer
- $\theta_{i,j}$: the threshold to choose between data rates $m_i$ and $m_j$ (i.e. $j < i$)

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Manuscript Received: Dec. 10, 2009
Revision Received: Mar. 10, 2010
and Accepted: Apr. 10, 2010