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Estimation of the Available Bandwidth for TCP and UDP traffic over 802.11 WLANs.

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Abstract—*Wireless bandwidth estimation is a critical issue for Quality of Service provisioning in IEEE 802.11 WLANs. Current bandwidth estimation solutions focus on either probing techniques or cross-layer techniques and either requires significant bandwidth resources or protocol modifications. To alleviate these problems, this paper proposes an analytical Model-based Bandwidth Estimation algorithm for multimedia services over the IEEE 802.11 networks. The MBE module for available bandwidth estimation is developed based on novel TCP/UDP throughput models for wireless data communications. The novel aspects in comparison with other works include the fact that no probing traffic is required and no modification of MAC protocol is needed. Extensive simulations and real tests were performed demonstrating that MBE has very good bandwidth estimation results for content delivery in conditions with different packet sizes, dynamic wireless link rate and different channel noise. Additionally, MBE has lower overhead and lower error rate than other state-of-the-art bandwidth estimation techniques.*
Index Terms: *Model, bandwidth estimation, TCP*

1. INTRODUCTION

Recently, an increasing number of rich media applications exchange data over IEEE 802.11WLANs. Bandwidth estimation schemes have been widely used to improve the Quality of Service (QoS) of multimedia services [1]. Shah et al. [2] utilize a novel bandwidth estimation algorithm and propose an admission control-based resource management approach to provide fairness of existing traffic. Li et al. [3] develop a play out buffer and rate optimization algorithm to improve the performance of video streaming service. The basic idea is to optimize the streaming bit-rate and initial buffer size based on the estimated wireless bandwidth. Efficient bandwidth estimation scheme is also significant for adapting the data transmission rate to the available bandwidth. Research in shows that the awareness of network resources can benefit the proposed QoS negotiation scheme that allows users to dynamically negotiate the service levels required for their traffic and to reach them through one or more wireless interfaces. Many bandwidth estimation techniques have been proposed to provide estimations in wired networks such as Spruce, Path load, path Rate, path Chirp, IGI/PTR, Sprobe, etc. However, bandwidth estimation in wireless networks is a more challenging issue due to flexible wireless conditions such as: increased and variable Packet Error Rate (PER), wireless link rate adaptation, signal fading, contention transmission retries, etc. Most of the existing wireless bandwidth estimation solutions such as WBest [and DietTOPP use probing-based techniques. Probing techniques introduce extra traffic which has a negative influence on the multimedia applications. Recently, mechanisms like iBE [and Idle Gap that employ cross layer based techniques have been proposed to estimate the wireless channel bandwidth. Unfortunately, the cross layer solutions require modifications of standard protocols which make it complex and not desirable. Current wireless bandwidth estimation solutions can be grouped into two categories: 1) **Probing-based Technique**. DietTOPP [estimates the available bandwidth by comparing the adapted probing rate and the corresponding throughput, in order to find out the turning point. WBest uses the packet-pair dispersion technique to estimate the effective capacity of the wireless networks and a packet train technique to infer mean and standard deviations of available bandwidth; 2) **Cross-layer Technique**. IdleGap introduces an idle module located between the link layer and network layer. The idle module obtains the wireless link idle rate from the Network Allocation Vector (and sends it to the application layer. The bandwidth is

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then computed using link idle rate and the known capacity. This paper proposes a **Model-based Bandwidth Estimation** algorithm to estimate the available bandwidth for data transmissions in IEEE 802.11 WLANs. There are three major contributions. First, MBE relies on a novel TCP model for wireless data communications, which extends an existing TCP throughput model by considering the IEEE 802.11 WLAN characteristics transmission error, contention, and retry attempts. Second, MBE utilizes a new UDP throughput model based on UDP packet transmission probability and IEEE 802.11 channel delay. Third, the paper derives a formula estimating the bandwidth when TCP and UDP traffic co-exists in IEEE 802.11 networks and proposes MBE. Note, unlike most existing estimation techniques, MBE neither require modification of current transmission protocols nor use the probing traffic.

In this paper, stand-alone and comparison-based experiments have been carried out using both simulations and real tests. MBE model is studied in terms of feedback frequency, variant packet size, dynamic wireless link rate and different wireless packet error rates. Furthermore, MBE is compared with existing wireless bandwidth estimation techniques using two performance metrics: error rate and overhead.

2. RELATED WORKS

This section presents the related works regarding MBE. To begin with, the existing bandwidth estimation solutions are introduced and then subsequently, current models for TCP throughput and IEEE 802.11 MAC are described. Finally, different wireless link rate adaptation algorithms are presented. MBE uses these related techniques for both model development and experimental design.

A. *Wireless Bandwidth Estimation Techniques*

Current bandwidth estimation solutions for wireless channel can be grouped into two categories:

Probing-based Techniques:

WBest [14] uses a probing packet-pair dispersion solution to estimate the effective capacity of the wireless networks. It uses a packet-train technique to infer mean and standard deviations of available bandwidth. However, WBest has not been compared with other wireless bandwidth estimation techniques. DietTOPP [15] dynamically changes the bit-rate of probing traffic. The available bandwidth is obtained when the probing traffic throughput experiences the turning point. The weakness of DietTOPP is the enormous amount of overhead introduced. Ad-hoc Probe sends fixed size and back-to-back probing packet pairs, from sender to receiver. The transmission time is stamped on every packet by the sender. The path capacity is then calculated at the receiver. However, the main limitation of Ad-hoc Probe is that it is only suitable for measuring the path capacity of fixed rate wireless networks. ProbeGap [12] probes for “gaps” in the busy periods and then multiplies by the capacity to obtain an estimate of the available bandwidth. The main disadvantage of ProbeGap is the dependency on other capacity estimation schemes.

Cross Layer-based Estimation Techniques

iBE [13] estimates the wireless network bandwidth using the packet dispersion technique which records the packet payload size and one way delay at the MAC layer. The estimation results are then sent to application layer for intelligent adaptation. iBE uses the application data packets themselves instead of probing traffic, reducing the estimation overhead. However, iBE requires modification of the 802.11 MAC protocol. IdleGap develops an idle module between link layer and network layer. The idle module obtains the link idle rate from the Network Allocation Vector and sends it to the application layer. The bandwidth is calculated using link idle rate and known capacity. Shah et al. [2] propose an estimation solution to capture the wireless channel conditions at MAC layer by measuring the channel busy time, and use it to infer the available bandwidth. The probing-based techniques rely on the probing traffic which impact the wireless communication services due to the additional data introduced. Significantly, the cross-layer techniques have lower overhead than packet dispersion solutions. However, they are difficult to be deployed widely due to the modifications required in the devices and standard protocols.

B. *Wireless Link Rate Adaptation*

IEEE 802.11a/b/g standards all provide multiple link rates. For instance, 802.11b offers four transmission rates: 11Mbps, 5.5Mbps, 2Mbps, and 1Mbps. Link rate adaptation algorithms have been developed to dynamically adjust the data rate. Auto Rate Fallback based solutions is one of the earliest rate adaptation algorithm. ARF increases the data rate after consecutive successful transmission and decreases the data rate when transmission error occurs. The limitation is that ARF selects a higher data rate whenever a fixed threshold of successful transmissions achieves. Adaptive Auto Rate Fallback is developed based on ARF to resolve the bit-rate selection problem. AARF increases the threshold exponentially whenever the transmission attempt with the higher rate fails. AARF resets the threshold to the initial value when the rate is decreased and thereby provides support to both short-term and long-term adaptation. However, both ARF and AARF do not consider packet loss due to collision, and therefore, cannot apply for multi-stations scenario. Receiver Based Auto Rate based solutions use RTS/CTS frames to deliver the negotiated maximum transmission rate to both senders and receivers.

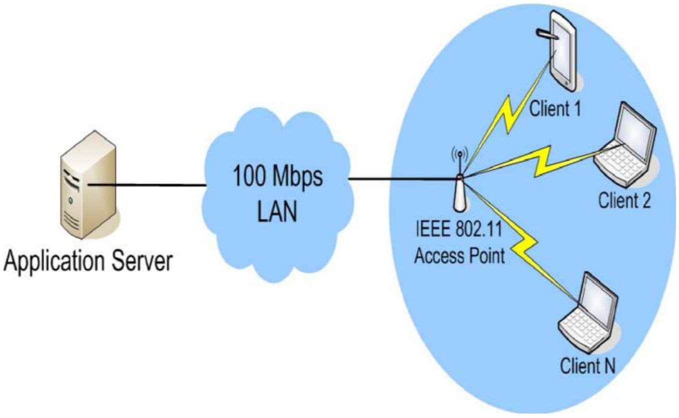

Figure 1: Network architecture of wireless bandwidth estimation.

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3. TAXONOMY OF BANDWIDTH ESTIMATION

This section provides taxonomy of all publicly available bandwidth estimation tools with the target bandwidth metric they try to estimate and the basic methodology used. Due to space constraints we do not provide URLs for these tools, but they can be found with any web search engine. An up-to-date taxonomy of network measurement tools is maintained on-line at

A. Per-hop capacity estimation tools

These tools use the VPS probing technique to estimate the capacity of each hop in the path. The minimum of all hop estimates is the end-to-end capacity. These tools require super user privileges because they need access to raw-IP sockets to read ICMP messages.

1. Pathchar was the first tool to implement VPS probing, opening the area of bandwidth estimation research. This tool was written by Van Jacobson and released in 1997. Its source code is not publicly available.

2. Pchar is another open source implementation of VPS probing. Libpcap is used to obtain kernel-level timestamps. Pchar provides three different linear regression algorithms to obtain the slope of the minimum RTT measurements against the probing packet size. Different types of probing packets are supported, and the tool is portable to most UNIX platforms.

B. End-to-end capacity estimation tools

These tools attempt to estimate the capacity of the narrow link along an end-to-end path. Most of them use the packet pair dispersion technique.

1. Bprobe uses packet pair dispersion to estimate the capacity of a path. The original tool uses SGI-specific utilities to obtain high resolution timestamps and to set a high priority for the tool process. Bprobe processes packet pair measurements with an interesting "union and intersection filtering" technique, in an attempt to discard packet pair measurements affected by cross traffic. In addition, bprobe uses variable-sized probing packets to improve the accuracy of the tool when cross traffic packets are of a few fixed sizes such as 40, 576, or 1500 bytes. Bprobe requires access only at the sender side of a path, because the target receives responds to the sender's ICMP-echo packets with ICMP-echo replies. Unfortunately ICMP replies are sometimes rate-limited to avoid denial-of-service attacks, negatively impacting measurement accuracy.

2. Path rate collects many packet pair measurements using various probing packet sizes. Analyzing the distribution of the resulting measurements reveals all local modes, one of which typically relates to the capacity of the path. Then path rate uses long packet trains to estimate the dispersion rate of the path. Is never larger than the capacity, and so provides a reliable lower bound on the path capacity.

3. Sprobe is a lightweight capacity estimation tool that provides a quick capacity estimate. The tool runs only at the source of the path. To measure the capacity of the forward path from the source to a remote host, sprobe sends a few packet pairs (normally TCP SYN packets) to the remote host. The remote host replies with TCP RST packets, allowing the sender to estimate the packet pair dispersion in the forward path. If the remote hosts run a web or gnutella server, the tool can estimate the capacity in the reverse path – from the remote host to the source – by initiating a short file transfer from the remote host and analyzing the dispersion of the packet pairs that TCP sends during slow start.

C. Available bandwidth estimation tools

1. Cprobe was the first tool to attempt to measure end to-end available bandwidth. Cprobe measures the dispersion of a train of eight maximum-sized packets. However, it has been previously shown that the dispersion of long packet trains measures the "dispersion rate", which is not the same as the end-to-end available bandwidth. In general the dispersion rate depends on all links in the path as well as on the train's initial rate. In contrast the available bandwidth only depends on the tight link of the path.

2. Path load implements the SLoPS methodology. Path load requires access to both ends of the path, but does not require super user privileges because it only sends UDP packets. Path load reports a range rather than a single estimate. The center of this range is the average available bandwidth during the measurements while the range itself estimates the variation of available bandwidth during the measurements.

4. EXPERIMENTAL SETUP AND SCENARIO

This section describes the experimental setup including the configurations for specific estimation tool. Three bandwidth estimation schemes which employ different types of techniques were selected for comparison. These include, non-probing technique-iBE probing based technique-DietTOPP and the cross-layer technique-IdleGap. iBE was implemented at the 802.11 MAC layer. The 802.11 WLAN was assumed to be the bottleneck link in the end-to-end path. The feedback frequency of iBE client was set to 10ms as indicated by the authors. RTS/CTS function was enabled to achieve best performance of iBE in all conditions. DietTOPP relies on probe packet size and cross-traffic, with the condition that the wireless link is the bottleneck in the end-to-end path. Hence, 1500 bytes probing packet and 250Kbps cross-traffic were used to obtain better estimation performance as indicated by the authors. IdleGap was implemented between 802.11 link layer and network layer. The cross-traffic for IdleGap was set to 10Kbps as suggested. Application packet size was set to 700 bytes since IdleGap achieved good accuracy for packet size ranges from 512 bytes to 896 bytes. RTS/CTS was also enabled.

The results of bandwidth estimation techniques such as iBE, DietTOPP, and IdleGap are as follows

Experimental Setup:

Each scenario included 15 cases with variable FTP/TCP and 6Mbps CBR/UDP traffic load. Test case 1 to test case 5 transmitted TCP traffic only, test case 6 to test case 10 transmitted UDP traffic only while test case 11 to test case 15 sent TCP and UDP traffic simultaneously. In order to estimate the maximum bandwidth a network can support, it is necessary to use high traffic load to saturate the 802.11 channel.

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In a saturated network, any new incoming traffic will decrease the overall throughput since the available throughput is higher than the network capacity. Based on tests scenarios A-1, A-2, and A-3, the feedback interval was set to 1.0s, packet size was 1000 Bytes and PER was set to 10^{-5}. The overall sending rate was greater than 6Mbps and less than 7Mbps. The mobile nodes are located close to AP at a distance smaller than 10m where the link data rate is 11Mbps. Testing time duration was 100s.

1: Error Rate Analysis:

Studies the error rate which reflects the accuracy . Shows the comparison results between bandwidth estimated and measured.

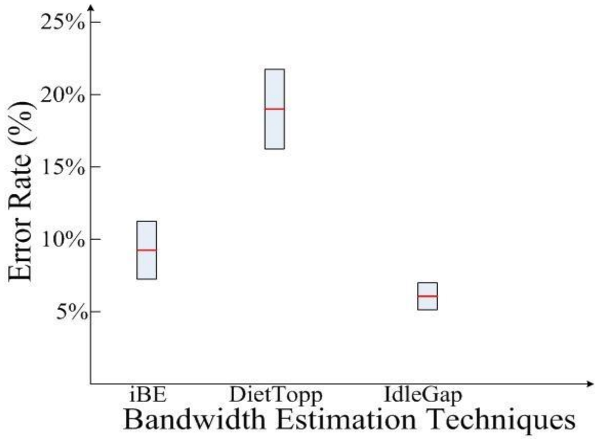

Figure 2: Error rate for iBE, DietTOPP, IdleGap

Experimental Result Analysis: Test cases were implemented to study the error rate of iBE under variable traffic load. In single flow situation. IdleGap provides better accuracy It is shown that the bandwidth estimated by the four algorithms and the bandwidth measured in simulation and real test all decrease as the overall traffic load increases.

2: Overhead Analysis:

The comparison results between bandwidth estimation techniques in terms of overhead.

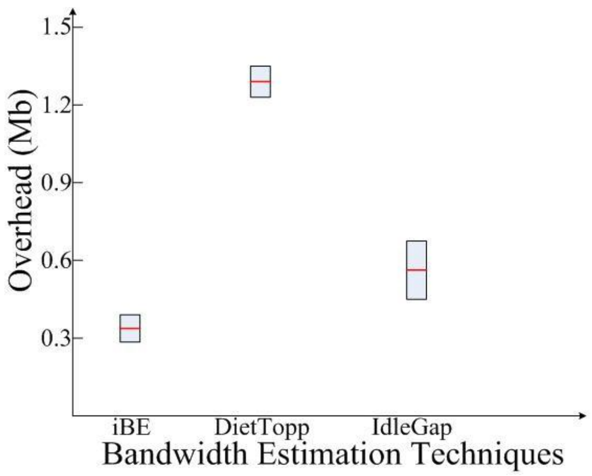

Figure 3: Overhead for iBE, DietTOPP, IdleGap

Experimental Result Analysis: For all the test cases, the overhead increases with the increasing number of contending flows. Among iBE, DietTOPP and IdleGap, DietTOPP created the highest overhead since DietTOPP continually sends probing traffic. iBE introduced low overhead, but MBE has 18% lower overhead than iBE, as it relies on small feedback packets.

3: Loss Analysis:

The results of the packet loss rate evolution with increasing number of UDP traffic flows when iBE, DietTOPP, IdleGap are used for bandwidth estimation.

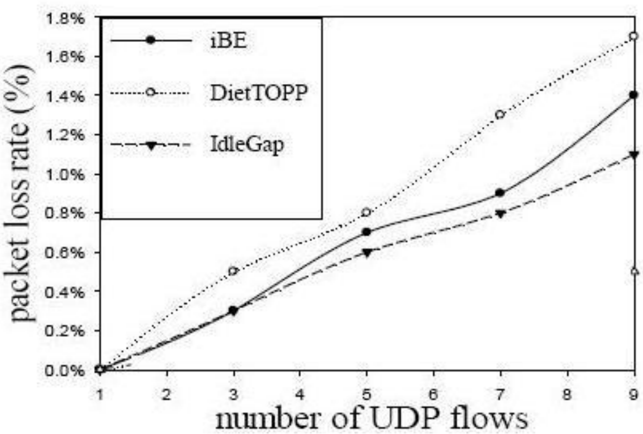

Figure 4: Packet loss rate of UDP for iBE, DietTOPP, IdleGap

Experimental Result Analysis: The number of UDP flows is increased from 1 to 9, and the bandwidth is estimated by four different bandwidth estimation schemes, iBE, DietTOPP, IdleGap and MBE. It is shown in Fig. 4 that DietTOPP produces the highest packet loss rate of up to 1.7% for 9 UDP flows, since DietTOPP continuously sends probing traffic which contends with the UDP traffic.

5. PROPOSED BANDWIDTH ESTIMATION ALGORITHM

This section introduces the architecture of the bandwidth estimation system and the details of the proposed bandwidth estimation algorithm.

1) Block-based System Architecture

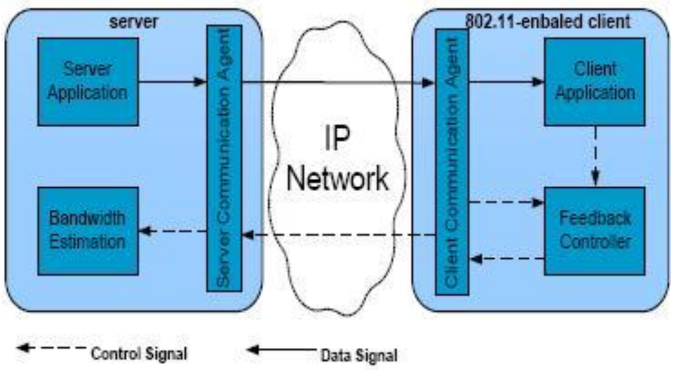

Figure 5: Block architecture of the proposed bandwidth estimation algorithm

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Fig. 5 presents the architecture of the proposed bandwidth estimation system which consists of two main building blocks: server side module and 802.11-enabled client side module. The server is responsible with sending multimedia traffic and estimating the achievable bandwidth of the 802.11 network. The client collects information of the delivered traffic, which is sent as feedback to the server. Multimedia traffic is delivered using TCP/IP protocol. Details of each sub-module in the proposed system are discussed next. The communication between the server application and client application uses a control communication link which is established when the client sends a TCP connection request to the server. Subsequently, the multimedia communication link is created between the server and client allowing for multimedia data transmission. The **Server Communication Agent (SCA)** and **Client Communication Agent (CCA)** located at both sides of the communication link are responsible with managing the transmission of multimedia traffic and control traffic. The SCA component maintains the sending buffer and forwards the feedback information received from FC to the **Bandwidth Estimation (BE)** component. The SCA also extracts the data size information and forwards to the BE component for bandwidth estimation.

Additionally, the **Client Application (CA)** component sends the client device's MAC address to FC and forward to SCA where the number of wireless clients is computed. The BE component then estimates the achievable bandwidth based on the feedback information. The details of the process in BE component are presented next

2) Bandwidth Estimation Algorithm

The proposed algorithm updates the TCP throughout model by considering the 802.11 MAC-based channel contention mechanisms.

A. TCP Over WLAN Throughput Model

There are three steps to update the original TCP model: 1) Packet Loss Update; 2) RTT Update; 3) Combination of TCP Model and 802.11DCF Model.

1. Packet Loss Update

Queue overflow-related loss and transmission loss are the major packet loss when transmitting TCP traffic in the wireless networks. The queue-related loss depends on the queue scheduling algorithm adopted. The widely used Random Early Discard (RED) queuing protocol is considered in this paper. RED determines the process of packet scheduling based on the current queue size (q_{k+1}) and updates the average queue size (q_{k+1}) for each arrived packet.

The average queue size is given in (1), where is the weight factor. q_w

$$\bar{q}_{k+1} = (1 - w_q)q_k + w_q \times q_{k+1} \qquad (1)$$

$$p_{cong} = \int_{0}^{1} \frac{\bar{q}_{k+1} - q_{min}}{q_{max} - q_{min}} \qquad (2)$$

The probability of packet loss caused by the RED queue (P_{queue}) is given in (2), where and denote the q_{min} and q_{max} denote the minimum and maximum threshold of the queue size

2. RTT Update

The end-to-end delay for TCP data transmission can be decomposed into seven components based on the OSI model:

1) Application Layer Delay (App_Delay) - the delay at application layer.
2) Transport Layer Delay (Transport_Delay) - the delay cost to implement transport protocol such as TCP congestion control.
3) Network Layer Delay (IP_Delay) - the delay at the IP layer for routing protocol.
4) MAC Layer Delay (MAC_Delay) - the delay caused by the backoff due to MAC-based channel contention.
5) Physical Llayer Delay (Phy_Delay) - the delay at physical layer depending on raw bits transmission type.
6) Propagation Delay (Prop_Delay) - the delay caused by data transmission over the channel medium. Propagation Delay is the function of data size and medium type.
7) Terminal Processing Delay (Proc_Delay) - determined by terminal's processing ability such as CPU, memory, power mode, operation system, etc.

There three states for the receiver**: idle, successful transmission and retransmission**, in a typical round-trip time (RTT). The delay for successful transmission is denoted as T_{succ}. Equation represent the 802.11 MAC layer delay for basic access mode (MAC_Delay$_{basic}$) and RTS/CTS mode (MAC_Delay$_{RTS}$), respectively, where DIFS (Distributed Inter-Frame Space) and SIFS (Short Inter-Frame Space) are contention control parameters defined in 802.11 MAC specifications. The parameter MAC_ACK represents the acknowledgment packet sent by the receiver of MAC layer.

$$MAC\_Delay_{basic} = DIFS + SIFS + MAC\_ACK \qquad (3)$$

$$MAC\_Delay_{RTS} = DIFS + 3*SIFS + RTS + CTS + MAC\_ACK \qquad (4)$$

B. TCP Throughput and IEEE 802.11 Models

This section first introduces the TCP throughput and the 802.11 models, which are used by the TCP over WLAN throughput model. The update processes for the two models are then described. MBE estimates TCP and UDP traffic separately. The behaviors of the TCP's fast retransmission and timeout mechanisms are captured in Kurose's model, which can be used to estimate the maximum bandwidth share that a TCP connection could achieve.

$$B = \frac{MSS}{RTT \times \sqrt{\frac{2bP_{tcp}}{3}} + T_0 \times min(1{,}3\sqrt{\frac{3bP_{tcp}}{8}} \times P_{tcp}} \qquad (5)$$

The TCP throughput model is described above where B is the throughput received, MSS denotes the maximum segment size, RTT is the transport layer roundtrip time between sender and receiver, b is the number of packets that are acknowledged by a received ACK, P_{tcp} is the steady-state loss

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probability, and T_0 is the timeout value to trigger retransmission.

C. *UDP Over WLAN Throughput Model*

We first propose the throughput estimation model for UDP over IEEE 802.11. Unlike TCP, the UDP protocol does not support packet retransmissions, and therefore, the UDP over WLAN throughput model should consider this. Hence, the terms P_{retr} and MRTT defined in which consider TCP fast retransmission and timeout respectively, should be removed in MBE's UDP version.The probability of retransmission when UDP traffic run over 802.11 networks can be written as

$$P_{retr}^{UDP} = P_{DCF} + P_{drop} \qquad (6)$$

The available bandwidth for UDP traffic over 802.11 WLANs is given in (7), shown below, where Payload is the total information in bytes, transmitted during one time period

$$B^{UDP} = \frac{\int_{T_0}^{T_1} \frac{Payload}{Delay\_UDP} dt}{T_1 - T_0} \qquad (7)$$

D. *MBE for Coexisting TCP and UDP Traffic*.

This section introduces MBE, which considers the combined effect of TCP and UDP traffic over WLAN and makes use of TCP and UDP over WLAN throughput models introduced before. When TCP and UDP traffic are transmitted together, their throughputs are different with those when TCP and UDP are delivered alone. TCP adopts a congestion control mechanism to adjust the transmission rate to the available bandwidth. UDP is more aggressive and always takes as much bandwidth as possible, therefore affecting the TCP traffic. The major difference between the models for TCP and UDP is with regard to consideration of lost packet retransmissions. To address this effect of UDP on TCP traffic, the weight w is introduced. By combining TCP and UDP over WLAN throughput models, the estimated aggregated throughput for coexisting TCP and UDP can be written as

$$B^{TCP+UDP} = w \times \sum_{i=1}^{N} B^{UDP} + (1-w) \times \sum_{j=1}^{N} B^{TCP} \qquad (8)$$

3) *Evaluation Metrics*

To evaluate the MBE performance, two estimation-based evaluation metrics were introduced: 1) error rate and 2) overhead.Error rate is defined as the difference between the MBE estimation results and the ground truth result. A lower error rate indicates higher accuracy of bandwidth estimation. The error calculation is given by

$$ErrorRate = \frac{|ESTIBandwidth - REALBandwidth|}{REALBandwidth}$$

Overhead is depicted as the total number of bytes sent by the model to perform the estimation. A lower overhead is critical for streaming applications over wireless networks.

6. CONCLUSION

Comparison with existing bandwidth estimation techniques such as iBE, DietTOPP, and IdleGap. Among the three compared techniques, IdleGap gives the smallest estimation error rate, and iBE introduced the lowest overhead.

This paper has proposed a novel MBE to estimate the available bandwidth for TCP and UDP traffic over 802.11 WLANs. MBE is based on novel throughput models for TCP and UDP traffic over IEEE 802.11 WLANs, which are also proposed

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