

Review of Bandwidth Estimation Tools and Application to Bandwidth Adaptive Video Streaming

Taner Arsan, Member IEEE
Kadir Has University
Computer Engineering Department
Cibali Kampusu 34083 Istanbul, Turkey
arsan@khas.edu.tr

Abstract – Streaming video is very popular in today’s best effort delivery networks. Streaming video applications should not only have a good end-to-end transport performance but also have a Quality of Service (QoS) provisioning in network infrastructure. Bandwidth estimation schemes have been used to improve the QoS of multimedia services and video streaming applications. To ensure the video streaming service quality, some other components such as adaptive rate allocation and control should be taken into consideration. This paper gives a review of bandwidth estimation tools for wired and wireless networks and then introduces a new bandwidth adaptive architecture for video streaming.

Keywords – Bandwidth Estimation, Video Streaming, Software Architecture

I. INTRODUCTION

Not only the rapid growth of wireless networks but also fast spread of multimedia applications provide Quality of Service (QoS) to become a very popular topic of current research in computer networks. Today’s technologies cannot provide the best solutions for video streaming users. In video streaming, it is not possible to use lower-layer transport layer protocols such as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), because TCP has huge delay while retransmitting the lost packets, and UDP does not guarantee packet delivery and packet loss recovery. Therefore an upper layer transport protocols such as Real-time Transport Protocol (RTP) and Real Time Control Protocol (RTCP) will be necessary. Although RTP is designed to provide end-to-end transportation and to support real-time applications, RTP does not guarantee the best video streaming performance. RTCP is a part of the RTP, and it provides feedback for monitoring the QoS. RTCP does not support all of control signaling requirements of applications. Therefore a session control protocols such as Real Time Streaming Protocol (RTSP) or a control mechanism is needed. RTSP is a session control protocol and its aim is to provide video streaming. These algorithms try to find a best solution for routing the packets, and best effort delivery, but none of them guarantees video streaming or briefly QoS routing. There should be an intelligent streaming media system to help regulating video streaming packets before or after routing of network devices for improving QoS to protect the important data in real-time, resource allocation, the

caching mechanism of the client and server and early warning of stream control and congestion control.

Video streaming system has some constraints such as bandwidth, congestion, and delay. The Internet has a heterogeneous structure and performance measurement is not considered as the primary goal of its architecture. End-to-end transport performance should be optimized for guaranteeing the video quality. It is possible to understand the network characteristics by using a bandwidth estimation tools. This qualification evaluates the performance of video streaming. On the other hand, the bandwidth utilization can be increased by using estimation tools [1]. Some bandwidth estimation tools consider bandwidth estimation techniques for networking solutions, but we need to consider bandwidth estimation tools as video streaming point of view in both wired and wireless networks. On the other hand, rate control and resource allocation should be used for the aim of maximizing the quality at the receiving side. So, streaming rate should be well regulated and should be optimized.

In this paper, a review for bandwidth estimation tools for wired and wireless networks. Then, a special architecture for bandwidth adaptive video streaming are introduced.

The rest of this paper is organized as follows. In the following section, methods used in video streaming are explained. We give a review of bandwidth estimation tools for both wired and wireless networks in Section 3. We introduce a new architecture for bandwidth adaptive video streaming system in Section 4. We conclude the paper with research contributions and future works in Section 5.

II. VIDEO STREAMING METHODS

Delivering video content over the Internet can be achieved by two methods: progressive download and real-time streaming. If the content size is short, the progressive download method is used. In this method, media content is directly downloaded from a server into storage units of a client, but in real-time streaming, client software plays media content without storing the content into any storage units. Real-time streaming can be easily explained as delivering media from a server to a client over a network in real-time. The client software is responsible for playing the media as it is delivered. There are two main types of delivery options for

real-time streaming: live and on-demand. If the media content contains live events, this type of streaming is called live streaming. On the other hand, if the media contents can be provided on user's demand, it is called on-demand streaming.

There are several common media streaming architectures available in the commercial use. Typical architecture is single sender - multiple receivers streaming system and it is shown for wired and wireless networks in Fig.1.

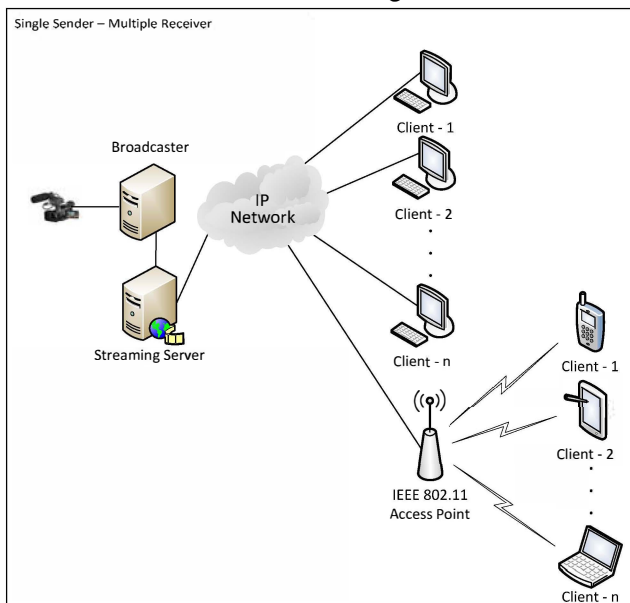


Fig.1. Video Streaming for Wired and IEEE802.11 Networks: Single Sender - Multiple Receivers.

III. REVIEW OF BANDWIDTH ESTIMATION TOOLS

Bandwidth is the amount of data that can be carried through a network connection in a given time period. It is often used as a synonym for data transfer rate. Some applications such as streaming video and streaming audio over a network require large bandwidth. In general, bandwidth estimation tools are used for analyzing network performance, optimizing end-to-end transport performance. On the other hand, bandwidth estimation schemes have been used to improve the QoS of multimedia services and video streaming applications. Different types of bandwidth estimation tools are developed so far for wired and wireless. Firstly, we have considered bandwidth estimation tools for wired networks.

A. Bandwidth Estimation Tools for Wired Networks

There are two major end-to-end measurement methods available in wired networks as Active Methods or Passive Methods.

1) Active Methods

In this method, the idea is to send dummy packets from sender node to receiver node. This method requires probing traffic. The aim of the method is to understand the network characteristics by the help of transmitted probing packets.

Four different types of techniques exist for active bandwidth estimation in wired networks such as Variable Packet Size (VPS) Probing, Packet Pair / Train Dispersion (PPTD) Probing, Self-Loading Periodic Streams (SLoPS) and Trains of Packet Pairs (TOPP). The aim of VPS probing is to measure the capacity of each hop along a path. The idea of the method is to measure the Round-Trip Time (RTT) from the source to each hop of the path as a function of the probing packet size. PPTD is used to measure the end-to-end capacity of a path. The source sends to the receiver multiple packet pairs which consists of two packets of the same size sent back to back. The dispersion of a packet pair at a specific link to the path is the time distance between the last bit of each packet. SLoPS is depended on a periodic packet stream concept. The source sends a periodic packet stream to the receiver at a certain rate. The method is based on variations in the one-way delays of the probing packets. Finally, TOPP sends many packet pairs at gradually increasing rates from the source to the sink.

There are several different classifications available by considering measurement metrics for active bandwidth estimation tools. These are Per-hop Capacity Estimation Tools, End-to-end Estimation Tools, Available Bandwidth Estimation Tools, TCP Throughput-Bulk Transfer Measurement Tools and Intrusiveness of Bandwidth Estimation Tools. Per-hop Capacity Estimation Tools use the VPS probing technique to estimate the capacity of each hop in the path. *Pathcar*, *Clink* and *Pchar* use VPS probing. End-to-end Estimation Tools attempt to estimate the capacity of the narrow link along an end-to-end path. Available Bandwidth Estimation Tools, TCP Throughput and Bulk Transfer Measurement Tools, Intrusiveness of Bandwidth Estimation Tools.

A classification of publicly available bandwidth estimation tools in wired networks is given in Table I [1]. *cprobe* [2] was the first end-to-end available bandwidth estimation tool in the literature. On the other hand, *treno* is the first tool to measure the Bulk Transfer Capacity of a path, and *cap* is the first canonical implementation of the Bulk Transfer Capacity measurement methodology. *NIMI* (National Internet Measurement Infrastructure) uses *cap* to estimate Bulk Transfer Capacity of a path. *Pathchar*, *pathload*, *Sting* and *pathchirp* are some popular examples for end-to-end bandwidth estimation probing methods [1].

cprobe [2] estimates the available bandwidth based on the dispersion of long packet trains at the receiver, but then it is shown that the dispersion of long packet trains does not measure the available bandwidth in a path: instead it measures a different throughput metric. It measures the dispersion of a train of eight maximum sized packets.

Pathchar is a tool that is to estimate Internet link characteristics by measuring the round trip time (RTT) of packets sent from a single host. It is possible to obtain the

per-hop capacity characteristics such as latency, bandwidth, queue and delays of any selected links. *clink*, *pchar* and *the tailgating* techniques are the examples of measuring the per-hop capacity methods. *Sting* is a TCP-based network measurement tool that measures the packet loss rate from sender to receiver and vice versa. *Sting* is developed under the lights of *NIMI* and it is similar to ICMP-based tools, but in this method TCP's error control mechanism can be used and it is possible to understand the direction in which a packet was lost.

TABLE - I
CLASSIFICATIONS OF BANDWIDTH ESTIMATION TOOLS FOR WIRED NETWORKS

TOOL	AUTHOR	MEASUREMENT METRIC	METHODOLOGY
<i>pathchar</i>	Jacobson	Per-hop Capacity	Variable Packet Size
<i>clink</i>	Downey	Per-hop Capacity	Variable Packet Size
<i>pchar</i>	Mah	Per-hop Capacity	Variable Packet Size
<i>bprobe</i>	Carter	End-to-End Capacity	Packet Pairs
<i>nettimer</i>	Lai	End-to-End Capacity	Packet Pairs
<i>pathrate</i>	Dovrolis Prasad	End-to-End Capacity	Packet Pairs & Trains
<i>Sprobe</i>	Saroiu	End-to-End Capacity	Packet Pairs
<i>Cprobe</i>	Carter	End-to-End Available BW	Packet Pairs
<i>Pathload</i>	Jain Dovrolis	End-to-End Available BW	Self-Loading Periodic Streams
<i>IGI</i>	Hu	End-to-End Available BW	Self-Loading Periodic Streams
<i>pathchirp</i>	Ribeiro	End-to-End Available BW	Self-Loading Packet Chirps
<i>Treno</i>	Mathis	Bulk Transfer Capacity	Emulated TCP Throughput
<i>Cap</i>	Allman	Bulk Transfer Capacity	Standardized TCP Throughput
<i>Sting</i>	Savage	Achievable TCP Throughput	TCP Connection
<i>Ttcp</i>	Muuss	Achievable TCP Throughput	TCP Connection
<i>lperf</i>	NLANR	Achievable TCP Throughput	Parallel TCP Connections
<i>Netperf</i>	NLANR	Achievable TCP Throughput	Parallel TCP Connections

Pathload is another active measurement tool that estimates the available bandwidth of a network path [3]. The main idea is that the one-way delays of a periodic packet stream show increasing trend, when the stream rate is larger than the available bandwidth. A sender process and a receiver process are running in *Pathload*. Periodic packet streams are achieved by UDP-User Datagram Protocol. On the other hand, TCP connection is used as control channel between two end-points. This algorithm has a very good approach for estimating bandwidth. It uses equation of $(R = L / T)$ where T is transmission period, L is packet size and R is the transmission rate. Minimum transmission period for back-to-back minimum-sized packets is around 15-30 μ s. Therefore

T_{min} is selected as 100 μ s. Minimum allowed packet size is 96bytes. At the beginning, L is set to 96bytes and considering target streaming rate, T is computed from the equation of $(R = L / T)$. In this point, it is also noted that selecting stream length as 100 packets rarely causes packet losses, and 100 packets also provides adequate number of delay measurements.

Pathchirp [4] is based on the concept of self-induced congestion and it is used the Self-Loading Periodic Streams methodology called self-loading packet chirps. *Pathload* [3] uses adaptive search method, for that reason it has a long convergence time. Both algorithms use different methodology, and their outputs are different from each other. *pathchirp* provides a single estimate of available bandwidth, whereas *pathload* provides minimum and maximum bounds on the available bandwidths. The idea of *pathchirp* is to use exponentially spaced highly efficient chirp probing train. The task is to estimate the available bandwidth over the path based on queuing delays of chirp probe packets transmitted from sender to the receiver and then conducting a statistical analysis at the receiver. As considered in most researches, congestion supposes to occur at the edge of the network close to the source or receiver. Data packets may encounter two congested queues, one on each end of their paths. *pathchirp* is a tool that presents a robust solution for these kinds of congested queues.

2) Passive Methods

While dummy packets are sent to receiver from sender in active methods, there is no injected packet in passive methods. The idea is to observe traffic already present in the network and then estimate the bandwidth of the network. This method considers Probability Distribution Function (PDF) of packet inter-arrival in a TCP flow. The PDF shows behavior of spike, spike bump, spike train and train of spike bumps. These characteristic behaviors are interpreted as a bottleneck with no substantial cross traffic, a low bandwidth bottleneck followed by a high bandwidth bottleneck, traversed bottleneck shared with a substantial amount of cross traffic and a low bandwidth upstream bottleneck shared with a substantial amount of cross traffic respectively.

In this method, one of the most important points is a clustering problem that detect shared bottleneck. In the receiving part of the end-to-end system, there is an observer that watches the arrivals of packets at some link. After all these steps, minimization of R enyi Entropy, which is a generalized version of Shannon Entropy formula, is used for discriminating between bottleneck sharing and non-sharing flows. Now the problem will change into an optimization (briefly a minimization) problem and then a cost function is selected and an algorithm for optimization is proposed.

B. Bandwidth Estimation Tools for Wireless Networks

Bandwidth estimation in wireless networks is more

challenging issue due to wireless conditions. Wireless networks have variable conditions such as wireless link rate adaptation, transmission retries, contention and variable Packet Error Rate (PER). Furthermore, the wireless channel is also a shared-access medium, and the available bandwidth also varies with the number of hosts contending for the channel. There are two major bandwidth estimation methods available in wireless networks as *Probing Techniques*, *Cross Layer-based Techniques* and *Model-based Techniques*. Although probing techniques need significant bandwidth resources, cross layer-based techniques are related with protocol modifications. Some newly proposed algorithms are suggested robust solutions for bandwidth estimation, and some details of these algorithms are given as Model-based techniques in this section. A classification of bandwidth estimation tools for wireless networks is given in Table II.

TABLE - I I
CLASSIFICATION OF BANDWIDTH ESTIMATION TOOLS FOR
WIRELESS NETWORKS

TOOL	AUTHOR	MEASUREMENT METRIC	METHODOLOGY
<i>Wbest</i>	Claypool	Per-hop Capacity	Packet Pairs & Trains
<i>DietTOPP</i>	Johnsson	Per-hop Capacity	Packet Pairs & Trains
<i>AdhocProbe</i>	Sun	Path Capacity	Packet Pairs & Trains
<i>ProbeGap</i>	Lakshminarayanan	Path Capacity	Packet Pairs & Trains
<i>iBE</i>	Yuan	End-to-End Capacity	Packet Dispersion
<i>IdleGap</i>	Lee	End-to-End Capacity	Link Idle Rate
<i>MBE</i>	Yuan	End-to-End Capacity	Model Based Algorithm

1) Probing Techniques

Most of the existing wireless bandwidth estimation solutions use probing techniques. *Wbest* [5], *DietTOPP* [6], *AdhocProbe* [7] and *ProbeGap* [8] are fundamental examples of this technique.

Wbest uses probing packet-pair dispersion solution to estimate the effective capacity over a flow path where the last hop is a wireless LAN. Secondly, a packet-train technique is used for estimating achievable throughput to infer the available bandwidth. The advantage of *Wbest* stems from avoiding a search algorithm to detect the available bandwidth by statistically detecting the available fraction of the effective capacity to mitigate estimation delay and impact of random wireless channel errors [5].

DietTOPP [6] uses probing packet-pair, but bit rate is changed dynamically. The available bandwidth is obtained when probing traffic throughput experiences the turning point.

AdhocProbe [7] 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 *AdhocProbe* is that it is only suitable for measuring the path capacity of fixed rate wireless networks.

ProbeGap [8] 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.

2) Cross Layer-Based Techniques

In general, Cross layer-based techniques are used for QoS provision in the scalable video streaming of high definition (HD) content. *iBE* [9] and *IdleGap* [10] are two examples of cross-layer estimation techniques for available bandwidth estimation.

iBE [9] 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 the 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 [10] develops an idle module between link and network layers. 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.

Probing-based techniques rely on probing traffic that impacts the wireless communication services due to the additional data introduced. Significantly, 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.

3) Model-based Techniques

Most of the existing wireless bandwidth estimation solutions focus on either probing techniques or cross-layer techniques and require either significant bandwidth resources or protocol modifications. To alleviate these problems, this paper proposes an analytical Model-based Bandwidth Estimation algorithm (*MBE*) for multimedia services over IEEE 802.11 networks. The *MBE* [11] module for available bandwidth estimation is developed based on novel transmission control protocol/user datagram protocol throughput models for wireless data communications. The novel aspects in comparison with other works include the fact that no probing traffic is required and that no modification of Media Access Control (MAC) protocol is needed.

IV. BANDWIDTH ADAPTIVE VIDEO STREAMING

In this study, as shown in Fig.2, a special architecture for bandwidth adaptive video streaming is implemented by using two different controllers: Bandwidth Adaptive Streaming

(BAS) controller and QoS controller. The outputs of these two controllers are collected at a Decision Center. Decision Center is the heart of rate optimization and resource allocation by considering bandwidth, delay and packet loss metrics.

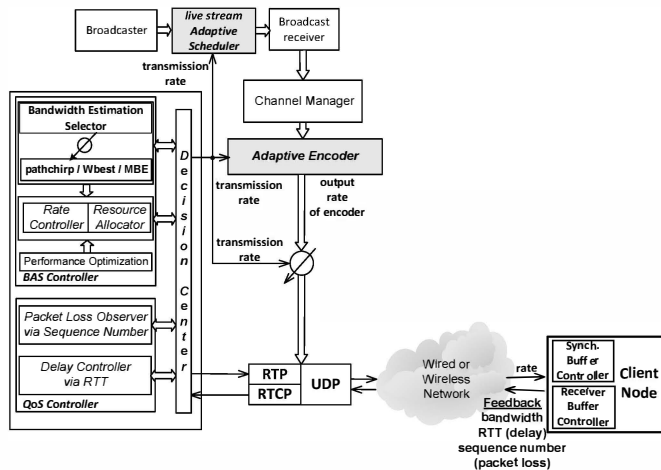


Fig.2. Bandwidth Adaptive Video Streaming Architecture

Firstly, the reference signal is set to a convenient value, and then Bandwidth Estimation tools called *pathchirp*, *Wbest* or *MBE* can be selected. Bandwidth estimation tool is one the most important agents in this system, because it determines available bandwidth and regulates reference signal. On the other hand, bandwidth estimation tool helps convenient path selection. Rate Control makes this procedure more intelligent. It has a performance index function to optimize the performance.

Secondly, we try to guarantee the QoS at the receiving side. We use the feedback signal of RTP called RTCP. RTCP includes the values for determining the values of packet loss rate and round-trip propagation delay. We have obtained these two values by the help of Packet Loss Observer and Delay Controller.

Finally, client node has also a decision center to regulate the packet-sending rate according to the number of data blocks stored in the client node which contains a synchronization and receiver buffer control. Synchronization buffer control stores the arriving packet to client node and forwards these packets to receiver buffer control.

BAS controller is responsible for end-to-end bandwidth estimation, adaptive rate control and multipath resource allocation. This controller also selects the best path to destination by using extended version of bandwidth estimation algorithm for effective video streaming. In order to control the rate and to assure the service quality, feedback of related metrics should be provided. BAS controller needs bandwidth estimation value to determine the path and to regulate and to allocate the resource.

Decision Center is the heart of this architecture, because all controller information is gathering here. It should therefore have a mechanism to determine optimal rate by considering

Bandwidth Adaptive Streaming Controller output (rate ratio) and QoS Controller outputs (delay and packet loss). Decision center also considers a performance index function. The constraints are also rate ratio, delay and packet loss. If other metrics are necessary such as jitter and congestion, it is also possible to calculate such these values by RTP/RTCP sender-receivers reports.

V. RESEARCH CONTRIBUTIONS AND CONCLUSIONS

In this study, a review of bandwidth estimation tools is given and a bandwidth adaptive video streaming architecture is introduced. This video streaming architecture includes Bandwidth Adaptive Streaming Controller, QoS Controller and Decision Center components and synchronization and receiver buffer controls in the receiving clients. While Bandwidth Adaptive Streaming Controller tries to obtain the best path, an acceptable rate and optimized resource allocation by using bandwidth estimation tools: *pathchirp*, *Wbest*, and *MBE*, the QoS controller calculates delay and packet loss values. Decision Center and client side buffers determine the path, and optimize the rate under the delay and packet loss constraints.

REFERENCES

- [1] R. S. Prasad, M. Murray, C. Dovrolis and K. Claffy, "Bandwidth estimation: metrics, measurement techniques and tools", IEEE Network, Nov 2003, Vol. 17, No. 6, pages 27-35.
- [2] R. L. Carter and M. E. Crovella. Measuring Bottleneck Link Speed in Packet-Switched Networks. In Perf.Evaluation,27,28,297-3,18, 1996.
- [3] M. Jain and C. Dovrolis, "Pathload: A measurement tool for end-to-end available bandwidth", In Proceedings of Passive and Active Measurements (PAM) Workshop, Mar. 2002.
- [4] V. Riberio, R. Riedi, R. G. Baraniuk, J. Navratil, and L. Cottrell, "pathChirp: Efficient Available Bandwidth Estimation for Network Paths." in Proc. 4th Passive Active Measurement Workshop - PAM2003, La Jolla, CA, Apr. 2003.
- [5] M. Li, M. Claypool, and R. Kinicki, "WBest: A bandwidth estimation tool for IEEE 802.11 wireless networks," in Proc. IEEE Int. Conf. LCN, Montreal, QC, Canada, Oct. 2008, pp. 374-381.
- [6] A. Johnsson, B. Melander, and M. Björkman, "DietTOPP: A first implementation and evaluation of a simplified bandwidth measurement method," in Proc. Swedish Nat. Comput. Netw. Workshop, Karlstad, Sweden, 2004.
- [7] T. Sun, G. Yang, L. Chen, M. Y. Sanadidi, and M. Gerla, "A measurement study of path capacity in 802.11b based wireless networks," in Proc. Int. Workshop Wireless Traffic Meas. Model., Seattle, WA, Jun. 2005, pp. 31-37.
- [8] K. Lakshminarayanan, V. N. Padmanabhan, and J. Padhye, "Bandwidth estimation in broadband access networks," in Proc. ACM SIGCOMM Conf. Internet Meas., Sicily, Italy, Oct. 2004, pp. 314-321.
- [9] Z. Yuan, H. Venkataraman, G.-M. Muntean, "iBE: A novel bandwidth estimation algorithm for multimedia services over IEEE 802.11 wireless networks" in Proc.12th IFIP/IEEE Int. Conf. Man. Multimedia Mobile Networks Services, Venice, Italy, Oct.2009, pp. 69-80.
- [10] H. K. Lee, V. Hall, K. H. Yum, K. I. Kim, and E. J. Kim, "Bandwidth estimation in wireless LANs for multimedia streaming services," in Proc. IEEE Int. Conf. Multimedia Expo., Toronto, ON, Canada, Jul. 2006, pp. 1181-1184.
- [11] Z. Yuan, H. Venkataraman, and G.-M. Muntean, "MBE: Model-Based Available Bandwidth Estimation for IEEE 802.11 Data Communications", IEEE Transactions on Vehicular Technology, Vol.61, No 5, June 2012.