Experimental Performance Evaluation of Bit-Rate Selection Algorithms in Multi-Vehicular Networks

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

IEEE 802.11 PHY supports multiple transmission rates according to multiple different modulations and coding schemes. Each WiFi station selects its own transmission rate according to its own algorithm; in particular, the IEEE 802.11 standards do not specify the bit-rate selection method. Although many adaptive bit-rate selection algorithms have been proposed, there is limited research and evaluation on the performance of such algorithms for roadside networks, especially in cases with multi-vehicle roadside multi-vehicular WiFi networks.

In this thesis we propose an opportunistic highest bit-rate algorithm, Opportunistic Highest Bit-Rate Multi-Vehicular WiFi Networks (OHBR-MVN), specifically for roadside multi-vehicular WiFi networks. Our proposal is based on three key characteristics of such networks: (1) vehicles will drive closer to, and eventually pass, the roadside WiFi station, experiencing a progressively better transmission environment; (2) the vast majority of data transmitted in single-vehicle drive-by downloading scenarios occurs at the maximum transmission rate; (3) vehicles that transmit at less than the maximum rate do so at the expense of those that could send more data at a higher transmission rate. We therefore believe that transmitting only at the highest possible bit-rate is the preferred algorithm for such networks. Further, this approach keeps the bit-rate selection extremely simple, avoiding the complexity and resulting problems of adaptive approaches.

Through a series of experiments that compare the throughput of both fixed and adaptive bit-rate selection algorithms we show that our approach yields both higher throughput and better fairness characteristics, while being significantly simple, and thus more robust.

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List of Acronyms

Acronym	Definition
AARF	Adaptive Auto Rate Fallback
AMRR	Adaptive Multi Rate Retry
AP	Access Point
ARF	Auto Rate Fallback
ASTM	American Society for Testing and Materials
BEB	Binary Exponential Backoff
BER	Bit Error Rate
BS	Base Station
BSS	Base Service Set
CARA	Context-Aware Rate Selection
CDMA	Code Division Multiple Access
CI	Confidence Interval
CSMA	Carrier Sense Multiple Access
CSMA/CA	CSMA Collision Avoidance
CSMA/CD	CCSMA Collision Detection
CTS	Clear to Send
DCF	Distributed Coordination Function
DSRC	Dedicated Short Range Communication
DSSS	Direct Sequence Spread Spectrum
ERP	Extended-Rate PHY
ESS	Extended Service Set
EWMA	Exponential Weighted Moving Average
GPS	Global Positioning System
HAL	Hardware Access Layer
HR	High-Rate
IEEE	Institute of Electrical and Electronics Engineers

LLC	Logical Link Control
MAC	Media Access Controller
MADWiFi	Multiband Atheros Drive for Wireless Fidelity
MDRS	Model-Driven Rate Selection
MIMO	Multiple Input Multiple Output
MV-MAX	Multi-Vehicular Maximum
OFDM	Orthogonal Frequency Division Multiplexing
OHBR	Opportunistic Highest Bit-Rate
OHBRDF	OHBR Detection Function
OHBR-MVN	OHBR Multi-Vehicular WiFi Networks
PCF	Point Coordination Function
PLCP	Physical Layer Convergence Procedure
PMD	Physical Medium Dependent
RBAR	Receiver Based Auto-Rate
RRAA	Robust Rate Adaptive Algorithm
RSSI	Received Signal Strength Indication
RTS	Request to Send
RTT	Round Trip Time
TCP	Transmission Control Protocol
SGRA	SNR-Guided Rate Adaptation
SNR	Signal-to Noise Ratio
SSID	Service Set Identifier
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
WAVE	Wireless Access in Vehicular Environment
WiFi	Wireless Fidelity

Chapter 1

Introduction

1.1 Motivation

Over the past years WiFi networking has evolved dramatically, having adopted and diversified itself with various services. For example, one of the areas is WiFi hotspots that enable people to get Internet connectivity in a public place or to receive information from that location using WiFi. A person can connect to the Internet in a public café or a community center through WiFi. A passenger on a plane or train can receive important or helpful information from the train station or at the airport [6] while waiting. Another example is vehicular networks.

There are several reasons and benefits that made WiFi networking become one of the major wireless networks. First, it is cheap to use. The users do not need to pay for using the wireless spectrum because of unlicensed bands, as compared to licensed network spectrums, such as cellular networks, that each carrier needs to purchase from the government. It is also cost effective to deploy and maintain the network, compared to other wireless technologies. Second, it provides the users high bandwidth compared to cellular networks. Third, it can be integrated easily with other networks, such as the Internet [6]. However, there are some issues. One of the most critical issues is the short-range coverage compared to cellular networks, which are intended to provide an ‘always on’ connectivity. Because of this issue, for a mobile WiFi station, communication with other WiFi stations may occur opportunistically within a very short period of time. Therefore, it is important to have a good mechanism that maximizes data transmission in the limited WiFi coverage during this short period.

The throughput of data transmission is one of the important attributes to measure the quality of a WiFi network. One of the factors to determine the throughput of data transmission in a WiFi network is transmission rate. WiFi networks support multiple transmission rates. 802.11b allows for using 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps. 802.11g supports 6 Mbps, 9 Mbps, 12 Mbps, 24 Mbps, 28 Mbps, 36 Mbps, 48 Mbps and 54 Mbps in addition to the bit-rates supported by 802.11b. 802.11a supports the same bit-rates that 802.11g supports. If the chosen transmission rate is lower than the best possible transmission rate, the spectrum is underutilized. Conversely, if it is higher than the best possible bit-rate, the transmission has a high error rate. Therefore, selection of an appropriate bit-rate is crucial in a WiFi network. In early WiFi networks, a single-fixed bit-rate selection algorithm was used (e.g., AT&T WaveLan [4] with 2 Mbps), but did not perform well in various network channel conditions. Nowadays, adaptive bit-rate techniques are used to improve performance under the frequently changing network channel conditions. Various adaptive bit-rate selection algorithms (e.g., SAMPLE) have been proposed, mostly for fixed (or stationary) WiFi client-based networks.

Vehicular networks are now becoming popular and crucial. Several wireless technologies, including WiFi, have been adopted to implement and deploy vehicular networks. Compared to other adopted wireless technologies, such as satellite and cellular, WiFi provides the benefits of being cost effective and having high bandwidth as mentioned above. There are two types of vehicular WiFi networks: vehicle-to-vehicle and roadside-vehicular WiFi networks. Vehicle-to-vehicle allows people to communicate with each other on the road through WiFi. Roadside vehicular WiFi networks enable cars on the road to access a WiFi Access Point (AP) at the roadside. In most cases, roadside vehicular WiFi networks are based on the Infrastructure WiFi mode, while vehicle-to-vehicle use the Ad-Hoc WiFi mode. Roadside vehicular WiFi networks are getting recognized as one of crucial and valuable WiFi networks.

In a roadside vehicular WiFi network, the WiFi clients move in/out. There are several common characteristics in the vehicular WiFi network, including fast mobility invoking very dynamic radio-channel condition and short-range opportunistic communication as the vehicles move fast. Hadaller et al. [2] described the characteristics of roadside vehicular WiFi networks in detail.

Like other WiFi networks, total throughput and fairness are the critical network attributes for vehicular WiFi networks and are used to measure the quality of the vehicular WiFi network:

1. Total throughput: Total throughput is the sum of each individual throughput which is an average rate of successful data transfer between a vehicular WiFi client and an AP. It focuses on the entire network. Distributed Coordination Function (DCF) is the main wireless media access method and enables packet-based fairness in WiFi networks, so it has the key role for throughput in WiFi networks. However, as a roadside AP is shared by all the associated vehicular WiFi clients, the lowest transmission rated vehicular WiFi client reduces the individual throughput of all other vehicular WiFi clients [2]. As a result, this *performance anomaly* [24] due to the packet-based fairness of DCF degrades not only individual throughput but also the total throughput in the vehicular WiFi client [2]. Roadside vehicular WiFi networks are more significantly affected by the *performance anomaly* because the short-range opportunistic communication of each WiFi client starts and ends with poor signal strength and

the lowest transmission rate [2]. Therefore, it is crucial to find and use an effective method that guarantees good total throughput in a vehicular WiFi network.

2. Fairness: Unlike the total throughput, fairness addresses maximizing individual throughputs fairly across all the vehicular WiFi clients in a vehicular WiFi network. Ideally, the best throughput performance in a vehicular WiFi network is when the individual throughput of each WiFi client is maximized while maximizing the total throughput of the network. Therefore, along with total throughput, fairness is an important factor to determine the quality of a vehicular WiFi network.

Therefore, it is worthy to research and find effective method for enabling high total throughput while maintaining good fairness in vehicular WiFi networks. There is some research [1, 2, 3, 29] focusing on the performance of a single vehicle WiFi client in terms of throughput, in roadside vehicular WiFi networks. However, there is no research, except Multi-Vehicular Maximum (MV-MAX) [1], which addresses the performance of roadside multi-vehicular WiFi networks in terms of throughput and fairness. MV-MAX is a Signal-to-Noise Ratio (SNR)-based medium-access method that opportunistically grants wireless access to vehicular WiFi clients with the best transmission rate and focuses on multi-vehicular WiFi networks in order to improve not only the overall throughput in the network but also the individual throughput for each vehicular WiFi client [2]. MV-MAX mainly focuses on modifying the scheduling of data transmission for all the attached vehicular WiFi clients. Transmission rate is a key to maintain effective total throughput and fairness. However, MV-MAX does not determine the transmission rate. That rate is determined by the underlying bit-rate-selection algorithm at the Media Access Controller (MAC) layer in the vehicle.

There was no research and evaluation of the transmission bit-rate algorithms for roadside multi-vehicular WiFi networks. As a result, it is not clear yet whether legacy adaptive bit-rate selection algorithms are effective for roadside vehicular WiFi networks or not. Moreover, it is also uncertain if the attributes used for determining the best transmission rate in fixed WiFi networks are sufficient enough for vehicular WiFi networks.

In addition, according to the paper of *Measurement based characterization of 802.11* [8], WiFi stations change their transmission rates very frequently. Half of the time WiFi clients send only one or two frames before switching again. This implies that the overhead caused by bit-rate switching is also significant. Therefore, some WiFi networks which may not need adaptive bit-rate algorithms can reduce the overhead of bit-rate switching. This is also a consideration to improve WiFi performance.

The research also shows that rate adaptation is less helpful when there is contention in the network. The paper insists that switching to a lower bit-rate due to packet losses without understanding the cause of the losses is unhelpful. This would be similar to Transmission Control Protocol (TCP) reducing its congestion window in response to all types of losses, which leads to unnecessary reduction in throughput when losses are not related to congestion. This means that in some multi-client-based WiFi networks, the adaptive bit-rate selection mechanisms may not be an effective way to determine transmission rate.

Therefore, it is very worthy to research and evaluate whether the legacy adaptive bit-rate selection algorithms are efficient for roadside multi-vehicular WiFi networks or not. Maybe, some fixed single bit-rate-based method could be better than the adaptive bit-rate selection algorithms in roadside vehicular WiFi network scenarios.

1.2 Contributions

Our study focuses on the experimental performance evaluation of bit-rate selection algorithms, specifically for roadside multi-vehicular WiFi networks. We conducted extensive experiments and analysis on not only the adaptive bit-rate selection algorithms but also the fixed bit-rates available in 802.11g.

We also propose a novel technique that considers opportunistic use of the highest bit-rate instead of the use of an adaptive bit-rate selection for vehicular WiFi networks. The technique also insists that utilizing of some network environment knowledge or characteristics, such as short opportunistic communication and predictable vehicle movement direction in a roadside vehicular WiFi network, can improve the performance of throughput and fairness significantly.

Our contributions are as follows:

1. Extensively conducted experiments and analysis in various roadside vehicular WiFi network scenarios. It helps any future relevant research in understanding and evaluating the performance of any legacy adaptive bit-rate selection algorithms.
2. Performance comparison between the adaptive bit-rate selection algorithms and the fixed bit-rate-based method with all the available bit-rates in 802.11g to find out the degree of efficiency of the adaptive bit-rate selection algorithms.

3. Introduction of a novel technique called OHBR-MVN in deciding and using the transmission rate at the MAC layer for a roadside vehicular WiFi network with the benefits of the performance efficiency and the simplicity of implementation.
4. Evaluation and demonstration of our proposal by comparing with other bit-rate selection algorithms.

In this thesis, we show that the greatest data transfer between a roadside AP and the vehicular WiFi clients only occurs when the vehicles use the highest bit-rate or do not transmit at all. This maximizes both the effectiveness of throughput and fairness in a vehicular WiFi network. In addition, it also provides simplicity to implement and deploy.

1.3 Thesis Organization

The rest of this thesis consists of the following chapters. Chapter 2 provides the background and the related work, including details of WiFi networks, transmission bit-rate selection, Multiband Atheros Driver for Wireless Fidelity (MADWiFi) and roadside multi-vehicular WiFi networks. Chapter 3 provides the details of OHBR-MVN. During our research we have conducted extensive experiments and analysis. In Chapter 4, we describe the details of the experiments. In Chapter 5 we describe the results and our analysis of the experiments. In Chapter 6 we present our conclusions. In Appendix (0) we show the data-transmission status diagrams for all the associated bit-rate selection algorithms in each test scenario.

Chapter 2

Background and Related Work

2.1 WiFi Network

In this chapter we review the basics of the WiFi network system with particular attention to DCF, which is one of important and fundamental attributes for our research. As our research addresses the performance of bit-rate selection algorithms at the 802.11 MAC layer, we also detail the bit-rate selection algorithms.

2.1.1 Architecture

IEEE 802.11 is the standard WiFi network technologies designed for providing almost the same experience as Ethernet. Data transfer over IEEE 802.11 networks requires three functional elements: wireless medium, WiFi station and WiFi backbone network.

- Wireless medium: the IEEE 802.11 working groups specified 802.11 wireless mediums as the 802.11 PHY. There are various 802.11 PHYs, such as, 802.11a, 802.11b, 802.11g, 802.11n, etc.

- Wireless station: Any network node connected to a WiFi network is called WiFi station. A WiFi station can transfer data with other WiFi stations over-the-air based on the 802.11 wireless medium. Examples of WiFi stations are WiFi-equipped desktops or laptops, WiFi-enabled Smartphones or WiFi APs. According to the WiFi network mode, either Ad-hoc WiFi mode or Infrastructure mode, each WiFi station plays a different role. In Infrastructure mode each WiFi station is categorized as an AP or a client. An AP, which is similar to a Base Station (BS) in cellular networks, enables associated WiFi clients to connect to the WiFi backbone network. The rest of the WiFi stations in Infrastructure mode are WiFi clients, which are networks nodes used by actual users, connect to the WiFi backbone network through APs. In Infrastructure mode a WiFi client can also communicate with other WiFi client peers in the network through its AP.

- WiFi backbone: In Infrastructure mode, a WiFi backbone network exists. The Basic Service Set (BSS) designates a WiFi network, which consists of AP(s) and WiFi clients. It is identified by a Service Set Identifier (SSID), which is the name of the WiFi network. The BSS is suitable when used in a small office or home. If a large WiFi coverage is required, multiple BSSs can be linked into an Extended Service Set (ESS) and all the APs in the ESS have the same SSID. An AP converts 802.11 wireless frames to other type of frames (e.g., Ethernet frame) and it also delivers to the WiFi backbone network.

Although many layers and components are required for a network, the IEEE 802.11 standard specified only PHY and MAC. The other layers and components are defined by other IEEE working groups and specifications; for example, 802.2 specifies Logical Link Control (LLC) and 802.1 specifies network management. Therefore, as a data link layer consists of both MAC and LLC, the IEEE specifications for the data-link layer of a WiFi networks are the combination of the 802.11 MAC and 802.2.

2.1.2 802.11 PHY

802.11 PHY is divided into two sublayers: Physical Layer Convergence Procedure (PLCP) and Physical Medium Dependent (PMD). PLCP is to converge between 802.11 MAC frames and wireless mediums, whereas PMD is to transmit WiFi frames over-the-air [6]. In order to transmit data over-the-air, IEEE 802.11 specifies the wireless mediums to be used and their usages as follows:

- 802.11 - Direct Sequence Spread Spectrum (DSSS): DSSS is a spread-spectrum technique to transmit a single bit over a wider frequency band. Initially, in 1997, 802.11 defined DSSS PHY with data rates of 1 Mbps and 2 Mbps.

- 802.11b - High-Rate (HR)/DSSS: In 1999, another PHY with data rates of 5.5 Mbps and 11 Mbps was specified in 802.11b and then DSSS was combined into a single interface and referred as 802.11b even though DSSS was not actually part of 802.11b. It has available 14 channels in the 2.4 GHz frequency band with each 5 MHz wide. For example, channel 1 is at 2.412 GHz, channel 2 at 2.417 GHz and so on up to channel 13 at 2.472 GHz. Channel 14 at 2.482 GHz is special for dedicating to Japan.

- 802.11a, 802.11h and 802.11j - 5-GHz Orthogonal Frequency Division Multiplexing (OFDM): In 1999 802.11a was defined based on 5 GHz. The PHY technology adopted OFDM as modulation technique and operates up to 54 Mbps. OFDM is a method for chopping a large frequency channel into a number of subchannels used in parallel. It is similar to Code Division Multiple Access (CDMA), but CDMA is based on more complicated mathematics than OFDM.

Each channel is 20 MHz wide and composed of 52 subcarriers. As a result of the success with the technology in North America, 802.11h for Europe and 802.11j for Japan were also defined.

- 802.11g - Extended-Rate PHY (ERP): 802.11g was motivated to obtain higher bandwidths than 802.11b, while retaining backward compatibility with 802.11b. It is almost identical to 5 GHz OFDM PHY and it offers the same bit-rate range. However, it is based on 2.4 GHz, which is the same frequency band as 802.11b, and also supports the same bit-rate range with 802.11b for backward compatibility. Therefore, 802.11g supports 1 Mbps, 2 Mbps, 5.5 Mbps, 6 Mbps, 9 Mbps, 11 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 48 Mbps and 54 Mbps.
- 802.11n - Multiple Input / Multiple Output OFDM (MIMO-OFDM): The early 802.11 PHY technologies (i.e., 802.11b, 802.11a and 802.11g) focused on performance improvements by making data transmission as fast as possible during the transmission time. However, unlike those technologies, initially 802.11n was targeted to achieve Ethernet throughput by subtracting all the overhead caused by the protocol management features, such as preambles, Inter-Frame Spacing and acknowledgements. 802.11n adopted MIMO technology to OFDM for much higher speed. It is very similar with OFDM, but it is based on a 2.4 GHz frequency band. Nowadays 802.11n can support up to 300 Mbps.

2.1.3 802.11 MAC

The 802.11 MAC layer locates on top of the PHY layer. It accesses the medium and transfer data over-the-air [6]. It also interacts with the WiFi backbone network. The 802.11 MAC is similar to Ethernet in the context of Carrier Sense Multiple Access (CSMA) to control access to the transmission medium as it was evolved from Ethernet, but it adopts Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) instead of Carrier Sense Multiple Access / Collision Detection (CSMA/CD).

The 802.11 MAC has some challenges that could impact data-transmission performance in 802.11 networks as follows [6]:

- Interference and noise at the radio-link: Unlike licensed wireless spectrum based networks such as cellular networks, unlicensed-wireless-spectrum-based networks need to consider significant and various interferences and noises. For example, as 802.11b/g shares the 2.4 GHz frequency band with microwave ovens and Bluetooth, any products and systems based on the technologies need to work around the radiation from microwaves and other Radio Frequency

(RF) sources. In 802.11 networks multi-path fading can also be a challenge as it can prevent data transmission over 802.11.

- Radio-link quality: Radio-link quality also impacts the data-transmission performance significantly. High-quality signals can transmit data at a high transmission rate, whereas low-quality signals transmit data at a low transmission rate. The distance between the WiFi stations is one of the major factors to determine radio-link quality. Each WiFi station needs to decide when and how to estimate the best possible transmission rate according to the radio-link quality and the wireless channel condition. The details of this transmission bit-rate change are described in Section 2.2.
- Hidden-terminal problem: Each wireless network has a coverage limit where a network node cannot directly communicate with another node if it is too far from that node. In this situation, the other node is called a hidden node or terminal. Collisions of data transmission resulting from hidden nodes can happen in a WiFi network. A resolution in 802.11 networks is to use Request to Send (RTS) / Clear to Send (CTS) signals between the involved nodes (i.e., the sender, the destination, and the hidden node). The sender sends the destination a RTS WiFi frame to prevent collisions caused by any hidden nodes before starting the actual data transmission. The destination responds to the RTS by sending a CTS WiFi frame. Then any WiFi stations which received only the CTS frame are hidden nodes and know a WiFi station (the sender) is ready to send data to the destination. Then the hidden nodes do not transmit data to the destination for the moment to avoid collisions. Use of RTS/CTS is optional in 802.11.

2.1.4 MAC Access Modes

In 802.11, a coordination function controls the wireless medium. There are several 802.11 MAC access modes or coordination functions:

1. Distributed Coordination Function (DCF): DCF is the mandatory coordination function for accessing the wireless medium in 802.11 and used for CSMA/CA. DCF checks if the radio-link is clear before transmitting a WiFi frame. Each WiFi station uses a random backoff after transmitting each frame to avoid collisions. DCF may also utilize RTS/CTS to prevent the hidden-terminal problem.
2. Point Coordination Function (PCF): PCF is an optional technology, according to the 802.11 specification, to enable contention-free service to the wireless medium. The technology ensures

that the wireless medium is used without any contention with other 802.11 wireless stations. It is similar to channel-based communications. Each WiFi station does not struggle to obtain the wireless medium. PCF requires a special point coordinator located in the AP. Because of this characteristic, PCF is available only in Infrastructure mode. PCF is not widely adopted and used.

3. Hybrid Coordination Function (HCF): HCF coordinates access to the wireless medium by using multiple service queues, so that each WiFi station can balance the queues for various applications. This is part of 802.11e which specifies quality-of-service for 802.11 [6].

2.1.5 WiFi Association

In Infrastructure mode, a WiFi client must associate with an AP. WiFi association is the initial process for a WiFi client to connect to a WiFi network. Logically, it is equivalent to a network node plugging a cable into Ethernet. During this process, some necessary tasks are performed, such as probing and WiFi authentication between the WiFi client and the AP. Once a WiFi association is established, the WiFi client can acquire an IP address if the address needs to be dynamically assigned.

2.2 Bit-Rate Selection

802.11 PHY supports multiple rates for data transmission according to the different modulation and coding schemes. In order to produce the highest throughput on the radio-channel condition with network environment varieties (e.g., location, quality of signal, fading, multi-path, mobility, hidden-terminal problem, etc.), each WiFi station needs to decide the best possible transmission rate statically or dynamically among the available transmission rates.

The transmission rate that a WiFi station determines can affect not only the performance of the individual throughput between the WiFi station and its receiver but also the overall throughput due to the performance anomaly caused by DCF [24]. If the transmission rate is higher than the best possible rate, the transmission error rate would be high. If the transmission rate is lower than the best possible rate, the data transmission would be underutilized. Therefore, to estimate and to use the best possible rate is crucial, but IEEE 802.11 standards do not specify the transmission-rate decision method. As a result, each WiFi protocol-stack implementation needs to support its own reliable and effective bit-rate selection mechanism, but it is not easy to estimate and decide on an appropriate transmission rate. The mechanism is placed in the WiFi MAC layer and should decide an appropriate transmission rate at a certain time according to one or more related network attributes such as SNR, Received Signal

Strength Indication (RSSI), transmission error rate, etc. In general, there are two approaches to decide transmission rate: fixed bit-rate, adaptive bit-rate selection algorithm.

2.2.1 Fixed Bit-Rate

A WiFi station can use a fixed bit-rate among the available bit-rates. Once a bit-rate is decided before or during a WiFi association is made, it will not be changed. The advantage of the fixed bit-rate is simplicity, but it may not be effective overall from the throughput perspective. If the fixed bit-rate is lower than the best possible transmission rate on the network channel condition, the performance of throughput on the WiFi station is underutilized. If the fixed bit-rate is higher than the best possible transmission rate, it causes significant data losses.

2.2.2 Adaptive Bit-Rate

In order to maintain the best transmission rate under time-varying WiFi network channel conditions the WiFi station can adapt the transmission rate. An adaptive bit-rate selection algorithm needs to evaluate the current radio-channel condition accurately, estimate an appropriate bit-rate, and then adjust the transmission rate accordingly. Although the idea is simple, it is not easy to figure out the current radio-channel condition accurately. There are also several challenges in adapting the transmission rate at a certain time [9]. First, it is difficult to estimate the best possible bit-rate to maximize the transmission throughput. Second, it is also difficult to decide when the bit-rate needs to be changed. In addressing these issues, a number of adaptive bit-rate selection algorithms have been proposed. An adaptive bit-rate selection algorithm can be categorized under one of the following approaches:

- Statistics based approach according to consecutive successes/losses or error rate; for example, Auto Rate Retry (ARF), Adaptive Auto Rate Retry (AARF), Adaptive Multi Rate Retry (AMRR) and ONOE. The sender utilizes long-term or short-term statistics from the past (consecutive) transmission results to determine adaptation of the transmission rate to the radio-channel condition change. For example, if the consecutive error rate has increased significantly, the transmission bit-rate may be dropped to the next lower bit-rate. Or, if the consecutive error rate is sufficiently lower for a while, the transmission bit-rate may be raised to the next higher bit-rate. However, there are some problems with this approach. One of the problems with this approach is decision inaccuracy of the transmission rate change. For example, if the error rate is increased, most of bit-rate selection algorithms in this approach reduce bit-rate to a lower bit-rate. However, the paper of *Measurement based Characterization of 802.11 in a Hotspot Setting* [8] shows that the rate reduction is wrong if the loss is made due to increased contention (not decrease of radio-signal quality) since the reduction of bit-rate increases contention by occupying the media longer and longer.

- Probing-based approach, which uses probe packets for sampling to estimate the best possible bit-rate. For example, SAMPLE, AMRR, Robust Rate Adaptive Algorithm (RRAA) and Context-Aware Rate Selection (CARA) [9, 12, 13, 14, 15].
- Signal (e.g., SNR or RSSI)-based approach, such as Receiver Based Auto Rate (RBAR) [31], SNR-Guided Rate Adaptation (SGRA) [14].

Overall it appears that adaptive bit-rate selection algorithms improve the throughput performance significantly. However, each algorithm has merits and drawbacks. Further an algorithm may show different performance in different network circumstances due to environmental variations.

2.2.3 ARF and AARF

Auto Rate Fallback (ARF) [9] was the first adaptive bit rate selection algorithm proposed and used for WaveLAN-II. At the beginning, ARF selects the highest bit-rate as the initial bit-rate and a timer is started. A sender adapts to the next higher transmission rate after a fixed number of successful transmissions (e.g., 10) at a given rate or the timer expires [12]. However, it switches back to the next lower rate after 1 or 2 consecutive failures. Once the bit-rate is changed, the timer is reset.

There are two problems with ARF. First, it does not perform well if the channel conditions change very quickly. Second, even though the channel condition does not change at all or change very slowly, it change it to the next higher bit-rate every 10 successful transmissions. As a result, it may increase error rate, and reduce the throughput [12].

Adaptive Auto Rate Fallback (AARF) [12] is an enhancement of ARF that addresses the latter of the above problems. To reduce this problem, it increases the number of consecutive successful transmissions before changing to the next higher bit-rate exponentially whenever the probing based on the higher rate transmission fails.

2.2.4 RBAR

Receiver Based Auto-Rate (RBAR) [31] is SNR-based adaptive bit rate selection algorithm by using RTS/CTS. It requires incompatible changes to the 802.11 MAC and PHY protocol. The interpretation of some MAC control frames is changed and each data frame must include a new header field.

In RBAR the rate adaptation mechanism is in the receiver instead of in the sender, by using RTS/CTR. The sender and the receiver exchange a pair of RTS/CTS before transmitting data. The receiver of the RTS frame calculates the highest bit-rate that would achieve Bit Error Rate (BER) less than 10^{-5} based on the SNR of the RTS frame [10, 31]. Then the receiver piggybacks the calculated bit-rate on the CTS frame. Then, the sender uses the bit-rate informed by the receiver.

2.2.5 AMRR

Adaptive Multi Rate Retry (AMRR) [12] is also a probing-based adaptive bit-rate selection algorithm and supported by MADWiFi. The algorithm utilizes not only long-term variations as the same as AARF [12] by using probing and Binary Exponential Backoff (BEB) but also short-term variations by simplifying the values of the bit-rate/transmission-count pairs in the MADWiFi algorithm. The MADWiFi algorithm has four bit-rate/transmission-count pairs (i.e., r_0/c_0, r_1/c_1, r_2/c_2 and r_3/c_3). Initially the bit-rate is r_0. If a transmission fails, it retransmits the data at r_0 up to c_0-1 times until succeeded. If it cannot succeed, it changes the bit-rate to r_1 and sends the data up to c_1 times and so on until the transmission at r_3 with c_3 times. The MADWiFi algorithm uses $c_0 = 4$, $c_1 = 2$, $c_2 = 2$ and $c_3 = 2$ as default values. However, to address short-term variations AMRR uses $c_0 = 1$, $c_1 = 1$, $c_2 = 1$ and $c_3 = 1$ instead. As a result, AMRR changes the bit-rate every time for each retransmission.

The rate r_3 is always set to be the lowest bit-rate. The rate r_0 varies and decided from the previous value of r0 and the transmission result during the sampling period [17]. The initial value of r_0 is 11 Mbps for 802.11b and 24 Mbps for 802.11a/g.

2.2.6 SAMPLE

SAMPLE (or SampleRate) [9] is one of the adaptive bit-rate selection algorithms supported by the MADWiFi driver used for AR5212-based devices (Section 2.3). It is a probing-based approach combined with the approach based on consecutive successes/losses. SAMPLE performs sampling for other bit-rates to update a record of that bit-rate’s consecutive losses rate. In the sampling, it periodically transmits packets (i.e., a probe request) with other higher bit-rates than the current transmission rate and estimates the per-packet transmission time of the other bit-rates. The per-packet transmission time, which includes retransmissions, of a bit-rate can be translated to throughput of the bit rate. If the estimate of other bit-rate’s per-packet transmission time is shorter than that of the current bit-rate, the current bit-rate is changed to the probed bit-rate. It implies that the current bit-rate is changed to another more suitable bit-rate as the estimated throughput of the other bit-rate is higher than that of the current bit-rate [9].

SAMPLE starts with the highest bit-rate and decreases the rate in steps until it finds a suitable one [16]. SAMPLE performs sampling only at the bit-rates whose throughput is better than the current bit-rate's throughput in order to prevent unnecessary bit-rate checkup with the lower bit-rates that do not fail packet transmission, but waste transmission time. SAMPLE stops probing at the bit-rate if it has several successive losses [9].

SAMPLE is relatively aggressive in selecting higher bit-rate among the adaptive bit-rate selection algorithms supported by MADWiFi such as AMRR and ONOE. It is willing to choose bit-rates with high loss rates if they have a lower expected transmission time than any other bit-rate. For example, suppose that 10 Mbps experiences the 20% loss rate, whereas 5 Mbps experiences no loss at all (0% loss rate). The transmission times of these bit-rates are approximates of 0.125 (1/Mbps), 0.2 (1/Mbps), respectively, so 10 Mbps with the 20% loss rate is better than 5 Mbps with the 0% loss rate in terms of transmission time. This implies that 10 Mbps with the 20% loss rate has higher throughput than that of 5 Mbps with the 0% loss rate. Therefore, SAMPLE will choose 10 Mbps.

2.2.7 ONOE

ONOE is a long-term statistics based adaptive bit-rate selection algorithm and is also supported by MADWiFi. The statistics is based on credit determined by the number of successful transmission, the number of erroneous transmission and the number of retransmission in a definite sampling period [16]. For successful transmissions at the current bit-rate, it raises the credit, and once the credit reaches a certain threshold, the current bit-rate is incremented to the next higher rate. For failure of transmissions and retransmissions at the current bit-rate, it deducts credit, and once the credit reaches below a certain threshold, the current bit-rate is degraded to the next lower bit-rate.

For the first packet to be sent to the receiver ONOE uses the initial transmission rate and the rate is different according to the WiFi technology. The initial rate for 802.11g and 802.11a is 24 Mbps, whereas 11 Mbps is used for 802.11b [9]. The algorithm initially sets to 0 for the credit, and then executes the following operations periodically (default period is one second):

- If no packet transmissions have succeeded during the period or 10 or more packets have been sent and the average of retries per packet is greater than one, ONOE degrades the bit-rate to the next lower bit-rate.
- If more than 10% of the packets need retry during the period, it decrements the credit by 1, but not below 0.
- However, if less than 10% of the packets need retry during the period, it increments the credit by 1. If the credit of the current bit-rate is equal to or higher than 10, it increases the bit-rate to the next higher bit-rate, and then resets the credit to 0.
- Otherwise, it continues at the current bit-rate.

ONOE always steps down or up one bit-rate during each period, so it gradually changes the bit-rate when the WiFi channel condition is changed. Therefore, ONOE is conservative in changing the bit-rate, compared to other algorithms such as SAMPLE and AMRR, as it is less sensitive in failure of individual packet transmission [16].

2.2.8 RRAA

Robust Rate Adaptive Algorithm (RRAA) [13] is also one of the adaptive bit-rate selection algorithms supported by MADWiFi and utilizes the statistics-based approach. However, unlike ONOE, the algorithm utilizes short-term loss ratio to assess the channel and adapt the transmission bit-rate to the dynamic change of the radio-channel condition. It also leverages an adaptive RTS filter to prevent collision losses with small overhead caused by decreasing rate.

The algorithm tries to maintain the stable rate in the presence of mild or random channel variations, but it quickly responds to the significant and obvious change of the channel condition. Especially, it quickly responds to the channel condition change due to mobility. For example, it responds rapidly when the user walks away/towards an AP. It also responds properly in the presence of the severe channel degradation due to the interference made by the hidden terminals, such as other WiFi stations, microwaves and cordless phones in the same frequency band by using the adaptive RTS filter.

The implementation of this algorithm consists of three modules:

- Loss Estimation to assess the radio-channel condition by keeping track of the frame loss ratio within a short time window. The window range is in between 5 and 40 frames.

- Rate Change to decide whether to change the rate based on the estimated loss ratio or not.
- Adaptive RTS Filter to selectively turn on RTS/CTS exchange in order to suppress collision losses.

2.2.9 MDRS

Model-Driven Rate Selection (MDRS) [3] is based on the loss-rate versus RSSI curves in a fact that in a mobile network error rate versus RSSI plots are consistent for each link rate across different scenarios. It is also based on the fact that the loss-rate and RSSI are predictable to model expected behavior [3]. The loss-rate versus RSSI is used in two ways.

- To make the sender estimate RSSI for the receiver.
- To make the sender decide the best transmission rate, given the estimated RSSI at the receiver and the model of loss rates.

MDRS mainly addresses vehicular WiFi networks. The approach adopted by this algorithm is similar with RBAR [18], but it does not need a receiver-to-sender control channel to inform the signal strength to the sender. Instead, it forces the sender to predict the signal strength so the algorithm can be easily deployed without significantly changing the involved WiFi stations. The algorithm requires change only in the WiFi driver at the sender. It does not require changes of any other things, such as protocols, standards, receivers and applications. Thereby, the algorithm should be well suited in AP at the roadside to transmit data to the passing vehicles.

MDRS permits the sender to infer the degree of signal asymmetry between the sender and the receiver, and then to dynamically determine the most appropriate data rate to adapt to the degree of asymmetry. The sender begins by assuming that the signal strength between the sender and the receiver is symmetric. However, over time MDRS adjusts the degree of symmetry for the signal strength between the sender and the receiver. The sender utilizes the signal strength of ACK frames arriving from the receiver for estimating the signal strength (i.e., RSSI) at the receiver [3].

The implementation of this algorithm consists of three modules:

- RSSI Estimation Module to assess the next RSSI based on previous, highly variable observations of RSSI values by using an Exponential Weighted Moving Average (EWMA): $RSSIest = ((RSSIest \times \alpha) + (RSSI \times (1.0 - \alpha))), \alpha = 0.50$.

- Asymmetry Estimation Module to determine the degree of asymmetry on the channel by comparing the observed loss rates with the loss rate estimated based on the model of loss rate versus RSSI curves.
- Rate Selection Module to select the best bit-rate by combining an estimate based on the next RSSI from the RSSI Estimation Module and the degree of asymmetry shift from the Asymmetry Estimation Module.

2.2.10 MV-MAX

Multi-Vehicular Maximum (MV-MAX) is the highest SNR based medium-access method that opportunistically grants wireless access to the vehicular WiFi clients being capable with the best transmission rate and focuses on roadside multi-vehicular WiFi networks to improve not only the individual throughput for each vehicular WiFi client but also the overall throughput in the WiFi network [2].

It is based on the fact that every vehicle eventually has good throughput performance when it is near the AP. However, according to the critical performance anomaly in WiFi networks due to DCF [24], when multiple vehicles are in the range of an AP, the vehicles on the fringe WiFi coverage area degrade the performance of all other vehicles. For this reason, MV-MAX does not allow a vehicle to transfer data with the AP when it has a poor signal quality. It permits data transfer only when the vehicle has a good signal quality (i.e., the highest SNR which roughly corresponds to the best transmission rate). With this way it is expected that not only every vehicle eventually gets individual throughput equally over the long term, but also the overall WiFi network throughput is dramatically increased [2].

MV-MAX does not determine the transmission rate. The rate is determined by the underlying bit rate selection algorithm at the MAC layer in the vehicle. However, MV-MAX modifies the scheduling of data transmission for all the attached vehicular WiFi clients. MV-MAX is similar with OHBR-MVN (Chapter 3), since both are opportunistic delay-tolerant communication based with the best transmission bit-rate, but OHBR-MVN uses the highest bit-rate and time fairness.

2.3 MADWiFi

There are many Atheros chipset based 802.11 products such as Atheros chipset based WiFi clients and APs. Multiband Atheros Driver for Wireless Fidelity (MADWiFi) [22] is a Linux based open source WiFi device driver for the Atheros chipset. MADWiFi is popularly used as most of the Atheros chipset based 802.11 products use it.

MADWiFi consists of two parts: open source based WiFi driver and Hardware Access Layer (HAL) which is a binary formatted library. The open source based WiFi driver accesses the WiFi chipset through HAL. Any WiFi network interface based on the MADWiFi driver uses prefix *ath*. Mostly, the interface is *ath0*, but some old versions use the prefix *wlan*.

2.4 Multi-Vehicular WiFi Network

One of the areas to which wireless networks have been applied is vehicular networks in various scenarios. Recently some of the car manufacturers have started adopting wireless network technologies in their cars. WiFi is one of the strongly considered technologies for vehicular wireless networks because of the several benefits. Compared to broadband wireless network technologies, such as cellular, WiFi is cost-effective (almost free) because of its operations in an unlicensed band, but higher bandwidth [26]. However, it is not feasible yet that it can be co-opted for vehicular networks due to short-range. It is almost impossible to make continuous connectivity. Its radio-channel condition is also not stable with highly dynamic and various interferences. Nevertheless, adoption of 802.11 to vehicular wireless networks would be a natural phenomenon along with the evolution of vehicular wireless networks. In the near future it is expected that WiFi networks will be spread rapidly in cars with other wireless devices such as the Global Positioning System (GPS) device and other smart devices with various wireless technologies and become one of the crucial WiFi networks [25].

In a vehicular WiFi network, the WiFi clients move in/out or around. There are several common characteristics in a vehicular WiFi network, including fast mobility invoking the dynamics of radio-channel condition and short-range opportunistic delay tolerant communication as the vehicles move fast. Because of these characteristics, some WiFi network attributes, such as transmission rate and roaming, need to be very actively adjusted.

Vehicular WiFi networks are different from fixed WiFi networks in which the WiFi clients are almost static. There are two communication types in vehicular WiFi networks: (1) vehicle-to-vehicle (or inter-vehicle) communication between vehicles and (2) roadside vehicular communication between a vehicle and a fixed roadside WiFi station. In most cases the Ad-Hoc mode would be used for the vehicle-to-vehicle communication, whereas Infrastructure mode is used for roadside vehicular communication. There are various 802.11 based technologies and standards for vehicular networks:

- Dedicated Short Range Communications (DSRC) is American Society for Testing and Materials (ASTM) standard E2213-03 based on IEEE 802.11a and it is allocated for the Intelligent Transportation System (ITS) communications [30].
- Wireless Access in Vehicular Environment (WAVE) is an operation mode used by WiFi devices to operate in the DSRC band [30]. Therefore, DSRC devices are IEEE 802.11 systems using the WAVE mode of operation in the DSRC band.
- IEEE 802.11p [27] is an approved amendment to the IEEE 802.11 standards to add WAVE and define enhancement to support ITS applications. It is based on ASTM standard E2213-03. It is used as the framework for DSRC and long/medium range architecture standard for vehicular networks, especially applications such as toll collection, vehicle safety services and commerce transactions via cars. 802.11p includes data exchange between the vehicles and between the vehicles and the roadside infrastructure in the licensed ITS band of 5.9 GHz (5.85 – 5.925 GHz).

2.5 Roadside Multi-Vehicular WiFi Network

Roadside multi-vehicular WiFi networks are a type of vehicular WiFi networks. Both of Ad Hoc mode and Infrastructure mode can be used for roadside vehicular WiFi networks, but Infrastructure mode is more practical. In an Infrastructure mode based roadside WiFi network, fixed WiFi stations at the roadside are usually APs and vehicular WiFi stations are WiFi clients. Unlike vehicle-to-vehicle WiFi networks, a roadside vehicular WiFi network has several key characteristics. Communication occurs between a vehicle and a fixed WiFi station at the roadside. It is has short opportunistic delay tolerant due to in the short-range WiFi coverage with the fixed WiFi station since the vehicular WiFi clients moves in/out very fast (e.g., 80 km/hour) in the coverage. Another characteristic is that the vehicular WiFi clients move along with the road, so their movement is predicable. Roadside vehicular WiFi networks can utilize these characteristics to improve their performance and the functionalities. For example, these characteristics can be used for the transmission bit-rate decision mechanism at the MAC layer to improve throughputs.

According to some prior research [2929], in a roadside vehicular WiFi network, each vehicular WiFi client experiences three phases.

- Entry phase: This phase starts when a vehicular enters into the WiFi network. In this phase, the WiFi client detects the signals from an AP and establishes a WiFi association. The WiFi client also establishes a TCP connection if necessary. When the WiFi association is established, the initial transmission rate is used. The initial bit-rate is usually higher than the best possible bit-rate at the fringe WiFi coverage in the vehicular WiFi network. For example, SAMPLE uses either 11 Mbps, 36 Mbps or 54 Mbps as the initial bit-rate based on the signal strength [2]. However, the best suitable transmission bit-rate just after the WiFi association establishment would be lower than the initial bit-rate chosen by SAMPLE. Therefore, the bit-rate selection algorithm may over-estimate the transmission bit-rate at the beginning of the entry phase. As the vehicle approaches the AP with the high speed, the signal strength will be increased rapidly, so the channel condition will be also changed rapidly. As a result, the transmission bit-rate should be increased rapidly.
- Production phase: Once the increasing signal strength reaches to a certain threshold that enables the vehicle to perform stable and effective communication with the AP, the phase is changed to the production phase. Obviously, in this phase the throughput is high. And relatively, loss rate and transmission delay are lower, compared to the entry phase and the exit phase.
- Exit phase: After the production phase, the vehicle enters the exit phase where the vehicle leaves the AP. The signal quality becomes decreased. The radio-channel condition is rapidly changed in the opposite way that happened in the entry phase and loss rate and transmission delay are increased again.

The most popular transactions in roadside vehicular WiFi networks would be downloading and uploading data. Even though a passenger can perform an interactive transaction such as web-browsing, it may not be practical due to the short-range WiFi coverage.

As many vehicular WiFi clients move in/out along the road, roadside multi-vehicular WiFi networks have a severe performance anomaly [24] due to the following reasons: (1) DCF provides throughput fairness that tries to make the individual throughputs of all the WiFi clients same. As a result, the wireless medium-access occupation time of high signaled WiFi clients is shorter, whereas the occupation time of the low signaled WiFi clients is longer [6]. (2) The characteristic of roadside vehicular WiFi networks that each vehicular WiFi client starts from the lowest transmission bit-rate when it enters the WiFi network [29]. This problem will be more severe when a network is dense with many vehicular WiFi clients.

Relatively, not much research and evaluation has been done in roadside vehicular WiFi networks in terms of throughput. Our research is focused on throughput in roadside multi-vehicular WiFi networks, especially the throughput performance with the transmission bit-rate selection at the MAC layer. We also address fairness of the individual throughputs across all the WiFi clients. We performed extensive experiments and analysis to learn about and improve the throughput performance in roadside vehicular WiFi networks.

Chapter 3

OHBR-MVN

3.1 Overview

Our research also proposes a novel technique, Opportunistic Highest Bit-Rate based Multi-Vehicular WiFi Network (OHBR-MVN), for roadside multi-vehicular WiFi networks to improve the overall throughput and fairness of individual throughputs across the vehicular WiFi clients.

Intuitively, in roadside multi-vehicular WiFi networks, the overall throughput would be high if an AP always sends WiFi frames with the highest bit-rate only to the capable vehicles. The individual WiFi client throughput would also be quite fair because the AP transmits the frames to all the vehicles since each vehicle should pass the AP with the capability of receiving with the highest bit-rate in a certain time period [2, 29].

OHBR-MVN is a simple data-transmission method (or bit-rate selection method) for sending WiFi frames to each vehicle at the highest bit-rate possible. The method manipulates the transmission bit-rate decision at the MAC layer and the packet scheduling at AP. The selected bit-rate according to OHBR-MVN is always the highest bit-rate in the WiFi network. For example, if the WiFi network is based on 802.11g, AP sends the frames with 54 Mbps if the vehicle is capable of receiving frames in the highest bit-rate. Otherwise, it does not send frames to the vehicle, and a result, the overall throughput performance in the network can be maximized.

3.2 Assumptions

OHBR-MVN is based on the following assumptions:

- Roadside multi-vehicular WiFi network: As this research focuses on roadside vehicular networks, it is expected that each vehicle transfers data with the highest bit-rate in a certain time period. When a vehicle approaches to the AP closely in the production phase, it should be capable of receiving data with the highest bit-rate.
- At least one available vehicle with the highest bit-rate capability at a time: As our research focuses on the problem of throughput and fairness in roadside multi-vehicular networks, single vehicle in WiFi coverage is not taken into account

3.3 Principles

- Opportunistic delay tolerant communication: AP performs data transfer only with the vehicles, which are capable of receiving data with the highest bit rate.
- Data transfer in the highest bit-rate: AP and all the highest bit-rate capable vehicles perform data transfer with the highest bit-rate only. In 802.11a/g data transmission is perform with 54 Mbps. In 802.11b AP sends WiFi frames with 11 Mbps.
- Time fairness to improve fairness of individual throughput across all the vehicles (Section 03.4.2).

3.4 Model

OHBR-MVN is composed of two functions: opportunistic highest bit-rate decision function, time-based fairness packet transmission scheduling function.

3.4.1 Opportunistic Highest Bit-Rate Decision Function

This function enables AP to keep track of the highest bit-rate capable vehicles and to determine WiFi frame transfer to the vehicles. The following diagram depicts the OHBR criteria and related parameters and values.

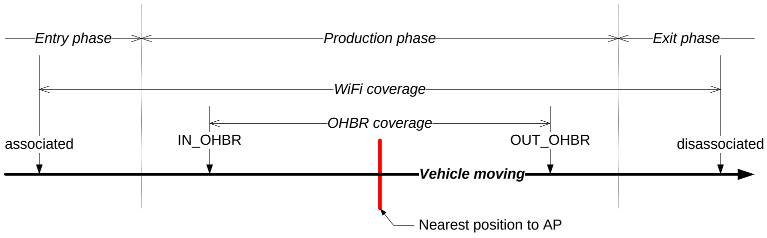


Figure 1: Model for Opportunistic Highest Bit-Rate Detection Function

OHBR coverage is the WiFi coverage area where a vehicle can receive data from AP in the highest bit-rate. OHBR capability is a measured value used to determine whether the vehicle is in OHBR coverage or not. *OHBR_Threshold* is a variable indicating the minimum required OHBR capability for a vehicle to reside in the OHBR coverage. If the OHBR capability of a vehicle is equal to or greater than *OHBR_Threshold*, the vehicle is in the OHBR coverage. Otherwise, the vehicle is out of the OHBR coverage.

Although a vehicle is associated with a roadside WiFi network, in OHBR-MVN the AP does not immediately send WiFi frames to the vehicle until it enters in the OHBR coverage. The AP has to wait until the vehicle enters into the OHBR coverage and it must know when the vehicle enters into the OHBR coverage. IN_OHBR is the point where the vehicle enters into OHBR coverage and it can start receiving WiFi frames from the AP at the highest bit-rate. IN_OHBR should be reliable and accurate as much as possible.

AP also must detect when the vehicle goes out of the OHBR coverage in order to stop sending WiFi frames. Once a vehicle enters in OHBR coverage, AP must keep track of OHBR capability of the vehicle to figure out if the vehicle reaches OUT_OHBR, which is the point where the AP stops sending data to the vehicle. Like IN_OHBR, OUT_OHBR should also be as reliable and accurate since the parameter directly and significantly affects the throughput performance for the vehicle. OHBR capability must be continually measured in an effective way to check the OHBR coverage state.

OHBR Detection Function (OHBFDF) is a function to determine the OHBR coverage state of a vehicle and it can be used to detect IN_OHBR and OUT_OHBR. The function must be reliable and accurate. There are various approaches to evaluate OHBR coverage, based on for example, RSSI, error rate, Probe request/response, or a combination of these attributes, so there could be various ways to implement OHBRDF. In this thesis, a RSSI based OHBRDF is introduced as an example (Section 3.5). However, in our experiments, a very simple OHBRDF that is based on the fixed distance and duration of OHBR coverage is used to evaluate the OHBR-MVN performance without any mistakes or inaccuracy caused by the implementation of OHBR-MVN. As there are many ways to implement OHBRDF, to find an effective and reliable function is a future research.

The following table was adopted from the table in [2] and it presents bit-rate decision functions in various methods including OHBR-MVN for roadside multi-vehicular WiFi networks.

Table 1: Rate coupling functions (*k* vehicles, *r*: bit-rate)

Method with available Rates	User Rate	System Rate

(r1, r2, …, rk)		
802.11	$\frac{1}{\sum_{j=1}^{k} \frac{1}{r_j}}$	K × User Rate
Time fairness	$\frac{r_u}{k}$	$\frac{1}{k}\sum_{j=1}^{k} r_j$
MV-MAX	$\begin{cases} r_u & if\ r_u = \max(r_1,...,r_k) \\ 0 & otherwise \end{cases}$	$\max(r_1,...,r_k)$
OHBR-MVN	$\begin{cases} r_u & if\ r_u = highest\ bit\ rate \\ 0 & otherwise \end{cases}$	$highest\ bit\ rate$

Hadaller et al. [2] introduces the formula of overall throughput by using each rate coupling function detailed in Table 1. Therefore, the overall throughput of each method in Table 1 can be computed by the formula with each rate coupling function.

3.4.2 Time-based Fairness Packet Scheduling Function

This function schedules packet transmission to the available vehicles fairly. Normally, this function will not be needed for the roadside WiFi network if it has only vehicular WiFi clients. This function is mainly applied when fixed WiFi clients are available. If the fixed WiFi clients are within the OHBR coverage which means the highest bit-rate coverage, the clients may occupy the AP all the time. As a result, the clients may severely affect fairness of individual throughputs across all WiFi clients.

In order to prevent this problem, a simple time-based fairness would be helpful for OHBR-MVN since it only allows for data transmission within a certain time period, MAX_OHBR_COVERAGE_TIME. Once MAX_OHBR_COVERAGE_TIME expires, the WiFi client backs off according to the following function:

BackOffTime = (*Number Of Highest Bit-Rate WiFi Clients – 1)* * MIN_BACKOFF_TIME

In above function, *NumberOfHighestBitRatedWiFiClients* indicates the number of the current available highest bit-rate capable WiFi clients. MIN_BACKOFF_TIME is a constant that the WiFi network can choose.

Most of data transmissions with the vehicular WiFi clients will not be affected by this scheduling function since the actual residence time within the OHBR coverage would be significantly shorter than MAX_OHBR_COVERAGE_TIME.

3.5 RSSI Based OHBR Decision Function

In this thesis, a simple RSSI and Probe request/response based OHBRDF is introduced as an example. The following diagram depicts the RSSI based OHBRDF.

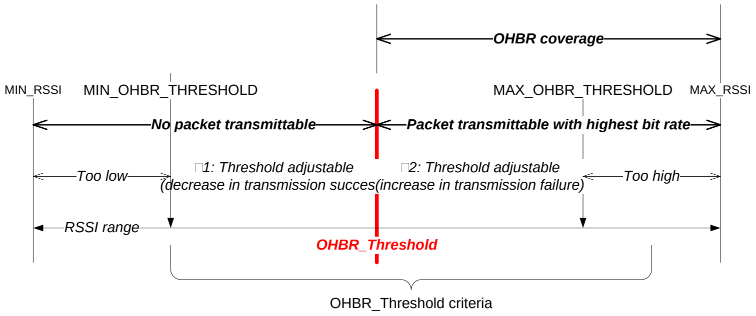


Figure 2: RSSI based OHBRDF

In this implementation RSSI is used to evaluate OHBR coverage state of the vehicle. *OHBR_Threshold* indicates the minimum RSSI that enables packet transmission to the vehicle in the highest bit-rate.

If the newly measured RSSI is equal to or higher than the threshold and the vehicle is currently out of OHBR coverage, credit is incremented by 1. If this happens consecutively for 3 times, the OHBR coverage state for the vehicle is changed to IN_OHBR_COVERAGE. Once the OHBR coverage state is changed to IN_OHBR_COVERAGE, AP starts sending packets to the vehicle at the highest bit-rate. If the newly measured RSSI is equal to or lower than the threshold and the vehicle is currently in OHBR coverage, credit is decremented by 1. If it happens consecutively for 3 times, the OHBR coverage state is changed to OUT_OF_OHBR_COVERAGE. Then AP stops sending packets to the vehicle. The following depicts the OHBR coverage state diagram.

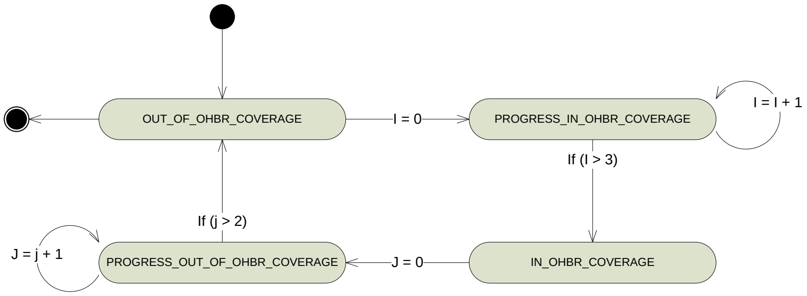


Figure 3: RSSI based OHBR coverage state machine

OHBR_Threshold can be adjusted in order to adapt to the channel condition and to increase accuracy of OHBR coverage evaluation based on RSSI by checking success/failure of data transmission or Probe request/response. If the packet (or Probe Request) transmission consecutively fails 3 times when the new *OHBR_Capability* is in between *OHBR_Threshold* and MAX_OHBR_THRESHOLD, *OHBR_Threshold* is adjusted with the new *OHBR_Coverage*. If the packet (or Probe Request) transmission succeeds 3 times when the new *OHBR_Capability* is in between MIN_OHBR_THRESHOLD and *OHBR_Threshold*, *OHBR_Threshold* is adjusted with the new *OHBR_Capability*.

The initial value of *OHBR_Threshold* selects the most efficient SNR value of the highest bit-rate from the WiFi data sheet of the AP. AP needs to periodically measure RSSI for the vehicle. AP measures RSSI from the acknowledgement of a data packet transmission to the vehicle. If there is no packet to be transmitted to the vehicle, AP periodically sends Probe Request to the vehicle and measures the response of the Probe Request. If the current RSSI is lower than *OHBR_Threshold*, AP also sends Probe Request periodically with the highest bit-rate since AP cannot send data to the vehicle and measure new RSSI. If AP does not receive acknowledgment, it treats the current RSSI as the new RSSI. Once new RSSI is measured, AP adjusts *OHBR_Capability* with the new RSSI. New *OHBR_Capability* is computed RSSInew in the following formula based on EWMA (Exponential Weighed Moving Average).

$$\mathit{OHBR\_Capability} = ((\text{newRSSI} * \alpha) + (\mathit{OHBR\_Capability} * (1.0 - \alpha))); \alpha = 0.50.$$

The following codes presents the logic of RSSI based OHBRDF.

```
IN_OHBR_COVERAGE = 1;
PROGRES_IN_OHBR_COVERAGE = 2;
OUT_OF_OHBR_COVERAGE = 4;
PREOGRE_OUT_OF_OHBR_COVERAGE = 8;

MAX_CREDIT = 2;
MIN_CREDIT = 0;
OHBR_Threshold = aGoodSNR;
OHBR_StateMachine = OUT_OF_OHBR_COVERAGE;
isInOHBRCoverage = false;
credit = 0;

while() {
        isTransmitted = sendPacket();
        newRSSI = getNewRSSI();
        OHBR_Capability = getNewOHBRCapability(newRSSI);

        if(isInOHBRCoverage) { // The vehicle is in the production phase
                //
                // Update credit to evaluate if vehicle enters the exit phase.
                if(OHBR_Capability <= OHBR_THRESHOLD) {
                        if( OHBR_StateMachine == PROGRES_OUT_OF_COVERAGE) {
                                credit--;
                        }
                        OHBR_StateMachine = PROGRESS_OUT_OF_COVERAGE;
                }
                else if(credit < MAX_CREDIT) {
                        credit = MAX_CREDIT;
                        OHBR_StateMachine = IN_OHBR_COVERAGE;
                }
                if(credit <= MIN_CREDIT) {  // Move to the exit phase
                        //
                        // Move to the exit phase.
                        isInOHBRCoverage= false;
                        exit();
                }
                // Adjust OHBR_THRESHOLD to up.
                if((isTransmitted == false) && (OHBR_Capability >= OHBR_Threshold)) {
                        if(OHBR_Threshold >= MAX_OHBR_THRESHOLD) {
                                OHBR_Threshold = MAX_OHBR_THRESHOLD;
                        }
                        else{
                                OHBR_Threshold = OHBR_Capability;
                        }
                }
        }
        else { // The vehicle is in the entry phase.
                //
                // Update credit to evaluate if vehicle enters the production phase.
                if(OHBR_Capability >= OHBR_Threshold) {
                        if( OHBR_StateMachine == PROGRES_IN_OHBR_COVERAGE) {
                                credit++;
                        }
                        OHBR_StateMachine = PREOGRES_IN_OHBR_COVERAGE;
                }
                else if(credit > MIN_CREDIT)
                {
```

```
                        credit = MIN_CREDIT;
                        OHBR_StateMachine = OUT_OF_OHBR_COVERAGE;
                }

                if(credit >= MAX_CREDIT) { // Move to the production phase
                        //
                        // Move to the production phase.
                        isInOHBRCoverage= true;
                }

                // Adjust OHBR_THRESHOLD to down.
                if((isTransmitted == true) && (OHBR_Capability <= OHBR_Threshold)) {
                        if(OHBR_Threshold <= MIN_OHBR_THRESHOLD) {
                                OHBR_Threshold = MIN_OHBR_THRESHOLD;
                        }
                        else {
                                OHBR_Threshold = OHBR_Capability;
                        }
                }
        }
}
```

Chapter 4

Experiments

4.1 WiFi Network

We conducted comprehensive experiments for studying the performance of various bit-rate selection algorithms in multi-vehicular WiFi networks (especially on the roadside) having the characteristic of rapidly changed wireless channel condition due to mobility. For the experiments we set up a testbed of roadside multi-vehicular WiFi networks with remote-controllable toy trains. The WiFi network is based on Infrastructure mode in 802.11g. The network consists of one WiFi AP and one or two WiFi clients, depending on the test scenario. Each WiFi station is a mini-box computer with an external antenna over a RF cable. The external antenna for the WiFi AP is placed at one end of the railroads used for toy trains. The cable length between the antenna and the AP mini-box is about 3 meters. There are two types of WiFi clients used in our experiments.

- Fixed (or stationary) WiFi client: The client is placed at the roadside in the middle of a train railroad. The distance between the client and AP is 4 meters. The distance is capable for the WiFi client to send data with 54 Mbps, so it is said that the client is in the highest bit-rate coverage area. This client is used to evaluate the performance of bit-rate selection algorithms for fixed WiFi networks. The client is also used in a combined WiFi network with a mobile WiFi client, which is one of practical multi-vehicular WiFi networks.
- Toy train based mobile WiFi client: Each train carries an external antenna connected to a WiFi client mini-box over an 8 meter RF cable so that the client moves by the toy train. This client is used to evaluate the performance of bit-rate selection algorithms in vehicular WiFi network scenarios such as single-vehicular WiFi networks, fixed-mobile WiFi networks and multi-vehicular WiFi networks.

Table 2: WiFi stations in the WiFi network testbed

Item		AP	WiFi client		
			Mobile - 1	Mobile - 2	Fixed
H/W	CPU	VIA Easter processor 1.2 GHz			
	Memory	906 MB			
	H/D	60 GB	40 GB	60 GB	
OS		Debian GNU/ Linux 4.1.1-21	Debian GNU/ Linux 5.0.4	Debian GNU/Linux 4.1.1-21	
WiFi	Chipset	Atheros (AR5413)			
	Card	EnGenius EMP-8602 miniPCI 802.11a/b/g			
	Antenna	7 dBi Pacific Wireless MA24-7N Magnetic mount external omnidirectional antenna			
	Cable	3.03 meters	9.06 meters	9.06 meters	3.03 meters
	Driver	MADWiFi 0.9.3			
Vehicle		N/A	Bachman White Pass Yukon toy train, G-Scale	Bachman North Pole Special toy train, G-Scale	N/A

4.2 MADWiFi

In our experiments, Linux based MADWiFi driver was used for the following reasons:

- Atheros chipset based WiFi NIC: The WiFi NIC in each WiFi station was Atheros chipset based, so MADWiFi is the appropriate WiFi driver with the chipset.
- Open source: Our experiments require changing the MAC layer, for example, use of different bit-rate selection algorithms. Therefore, open source based WiFi driver needs to be used.
- Easy and quick to use many different WiFi bit-rate selection algorithm.
- Many popular bit-rate selection algorithms embedded in MADWiFi. MADWiFi provides various bit-rate selection algorithms (SAMPLE, AMRR, RRAA and ONOE) as defaults.
- Easy and quick to support new WiFi bit-rate selection algorithm: MADWiFi is open source, so it is easy to add other bit-rate selection algorithms such as MDRS.

4.3 Bit-Rate Selection Algorithms

In our experiments, three different transmission bit-rate handling methods were tested (18 different bit-rate selection methods):

- Fixed bit-rates: 1 Mbps, 2 Mbps, 5.5 Mbps, 11 Mbps, 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 48 Mbps and 56 Mbps.
- Adaptive bit-rate selection algorithms: SAMPLE, AMRR, RRAA, ONOE and MDRS.
- Adaptive opportunistic fixed bit-rate: OHBR.

4.4 Operating Attributes

There were various attributes determined regarding WiFi network and packet transmission, for performing our experiments.

Table 3: Experiment operating attributes

Attribute		Synopsis
Pre-condition	WiFi interface	Before starting each test, WiFi interface at AP was reset.
	Bit rate selecton	Before starting each test, a bit rate selection algorithm in AP was randomly selected.
Data transfer	WiFi channel	Channel 4 (i.e. 2.422 Mhz) or 8 (2.475 Mhz), depending on the radio channel condition.
	Sender's transmission power	11 dBm was used (among the range of 0 and 19 dBm in MADWiFi). Along with the WiFi channel, this parameter was very critical in order to get a proper WiFi network test bed within the narrowed space.
	Receiver's transmission power	19 dBm.
	Transfer direction	AP to WiFi client.
	Utility	*iperf* . *Iperf* server at WiFi client and *iperf* client at AP.
	Packet type	UDP.
	Method	Unicast. AP sends unicast UDPs to all the available WiFi clients by using *iperf* .
	Transmission rate at network layer (IP)	54 Mbps
	Transmission rate at MAC layer (WiFi)	Vary and/or adaptive, according to the bit rate selection algorithm in AP. Therefore, the actual transmission rate over-the-air is determined by the bit rate selection algorithm in the AP.

4.5 Scenarios

Prior to evaluating the performance of bit-rate selection algorithms for multi-vehicular WiFi networks in various scenarios, we also measured the performance of bit-rate selection algorithms for single WiFi client based WiFi networks with several scenarios for several reasons. First, although there were many single WiFi client based performance measurements already produced by previous researches, it would be worthy to understand and verify the performance of each bit-rate selection algorithm in the same test environment without having any interference made by other WiFi clients since it would be the basis to compare and understand the performance of each bit-rate selection algorithm in multi-vehicular WiFi networks. Second, by comparing with the performance of single WiFi client based WiFi networks, it may help identify the factors and attributes that can affect the performance of data transmission in multi-vehicular WiFi networks coupled with the bit-rate selection algorithm, for example, packet scheduling. There are two scenarios for single client based WiFi networks: single-fixed (WiFi client based) WiFi networks and single-vehicular (WiFi client based) WiFi network.

For each experiment 12 fixed bit-rates (1 Mbps, 2 Mbps, 5.5 Mbps, 11 Mbps, 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 48 Mbps and 54 Mbps) and 5 adaptive bit-rate selection algorithms (SAMPLE, AMRR, RRAA, ONOE and MDRS) were used. Thereby, for each test in each experiment, one of the fixed bit-rates or an adaptive bit-rate selection algorithm was used. Each experiment was performed in 10 iterations, so 170 tests were performed for each experiment. In order to eliminate any dependency or influence between the consecutive tests, the test order of each bit-rate selection algorithm within each iteration was randomly selected.

4.5.1 Single-Fixed WiFi Network

One of the single WiFi network scenarios is the performance measurement of bit-rate selection algorithms in a single-fixed WiFi network. This scenario focused on the performance of each bit-rate selection algorithm in a fixed WiFi client network without having any interference from other WiFi clients. The experiment result was used to compare with the performance in other various vehicular WiFi networks, such as single-vehicular WiFi network, multi-vehicular WiFi network and fixed-mobile WiFi clients. It would be worthy of figuring out the performance difference of bit-rate selection algorithms between mobile WiFi networks and fixed WiFi networks.

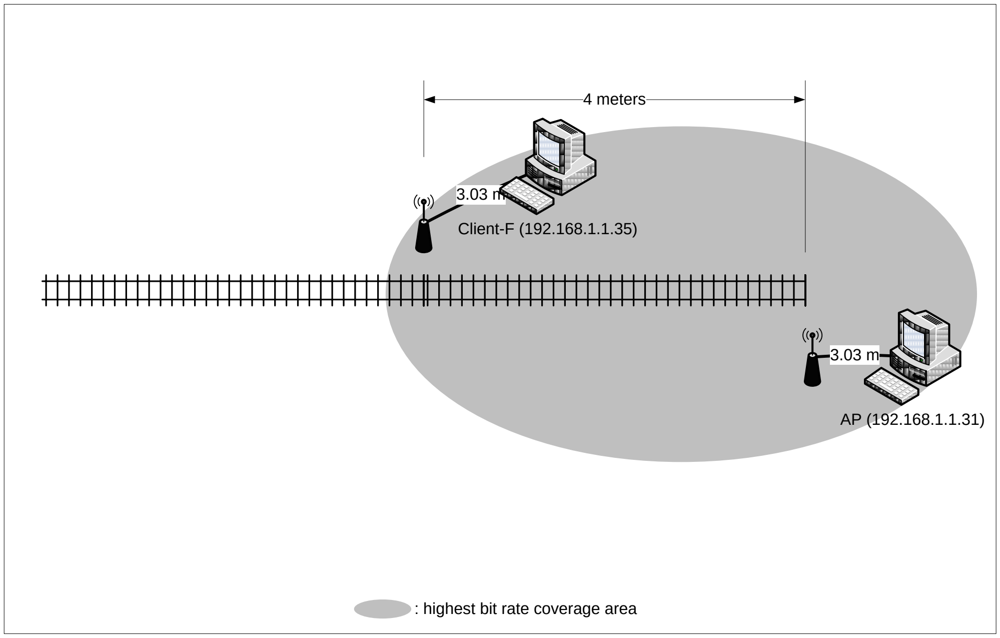


Figure 4: Single-fixed WiFi client based testbed

In this scenario, the fixed WiFi client is placed in the highest bit-rate (54 Mbps) coverage area in the distance of 4 meters with the AP.

The WiFi AP sent the WiFi client unicast UDP packets in 54 Mbps at the network layer for 30 seconds by using *iperf*, but the packets were transmitted according to the bit-rate at the MAC layer. The transmission power at AP was 11 dBm. WiFi channel 4 was used.

4.5.2 Single-Vehicular WiFi Network

We also measured the performance of bit-rate selection algorithms in a single-vehicular WiFi network. Similar to the scenario for single-fixed WiFi networks, this scenario focused on the performance of each bit-rate selection algorithms for vehicular WiFi network environment without having any interference from other WiFi clients. This experiment result was used to understand the performance difference between the scenario in single-vehicular WiFi networks and the scenario in multi-vehicular WiFi networks. In addition, it also helps find the factors and attributes that affect the performance of bit-rate selection algorithms in multi-vehicular WiFi networks.

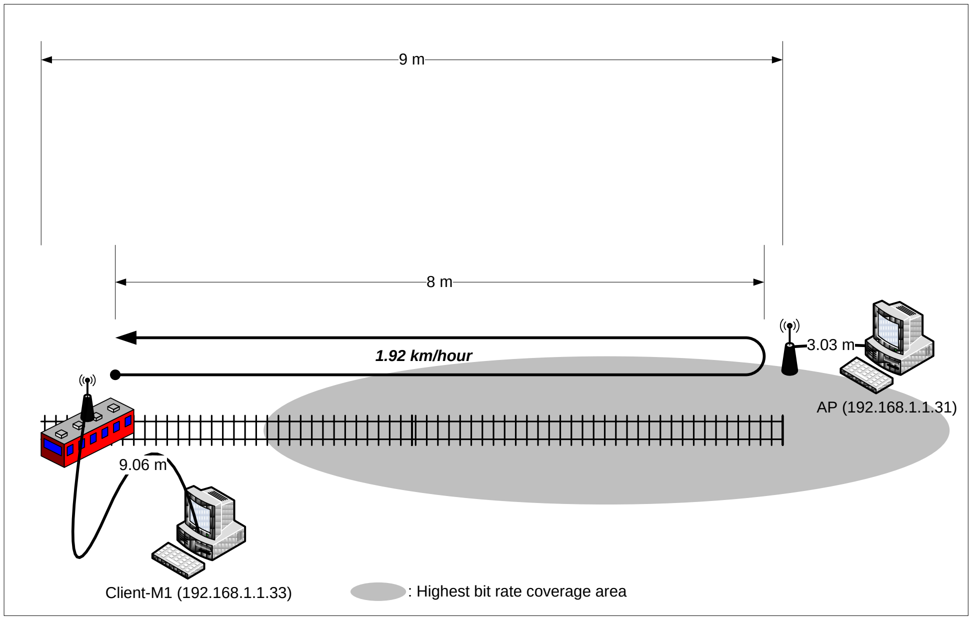


Figure 5: Single-vehicular WiFi client based testbed

Like the single-fixed WiFi network scenario, there were 10 iterations of 17 tests that were performed with 12 fixed bit-rates or 5 adaptive bit-rate selection algorithms. The maximum distance between the AP and the WiFi client is about 9 meters. The train starts moving from the end of the railroad toward the AP and turns back to the starting point when it almost reaches the AP, so it simulates the practical situation of a roadside vehicular network with an AP which locates at the roadside.

In this scenario, the best bit-rate measured at the starting point was about between 12 and 24 Mbps. The WiFi client always experienced entering the highest bit-rate coverage area, which is one of the characteristics for roadside vehicular WiFi networks. The maximum distance of the highest bit-rate coverage area between AP and the WiFi client was about 5 meters. The Round Trip Time (RTT) of the train movement was about 30 seconds, so the speed was about 1.92 km/hour. The AP sends the WiFi client unicast UDP packets in 54 Mbps for 30 seconds by using iperf at the network layer. The transmission power at AP is 11 dBm. WiFi channel 4 was used.

4.5.3 Fixed-Mobile WiFi Network

There are several scenarios in our experiments to study roadside multi-vehicular WiFi networks: fixed-mobile WiFi networks, multi-vehicular WiFi networks. In the scenario for fixed-mobile WiFi networks, fixed WiFi clients and mobile WiFi clients exist simultaneously. The focus in this scenario is to figure out the performance of bit-rate selection algorithms in a vehicular WiFi network when some fixed WiFi client(s) is connected to the vehicular WiFi network. The situation with hidden terminal is also taken into account in this scenario as well.

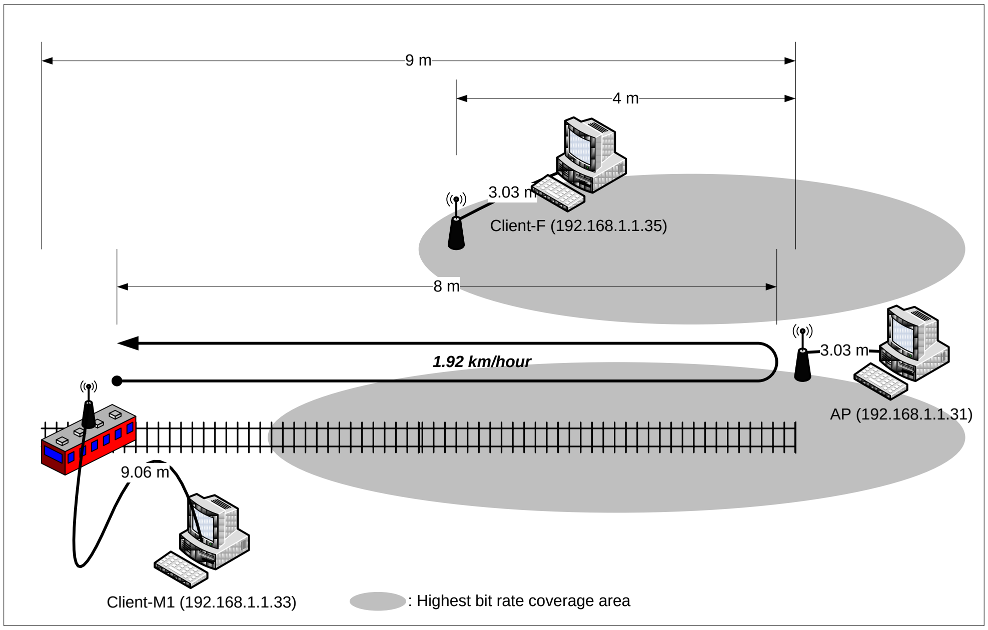


Figure 6: Fixed-mobile WiFi clients based network test bed

In this experiment, two WiFi clients were used. One was a fixed WiFi client residing at the roadside in the middle of the railroad, about 4 meters apart from AP. It was placed within the highest bit-rate coverage area that enables to transmit data with 54 Mbps. The other was a vehicular WiFi client based on remote-controllable toy train and exactly the same as the one for the single-vehicular WiFi network scenario. Therefore, the best bit-rate at the starting point was about between 12 and 24 Mbps. And the maximum distance of the highest bit-rate coverage area between AP and the WiFi client is about 5 meters. The RTT of the train movement was about 30 seconds, so the speed was about 1.92 km/hour.

AP sent unicast UDP packets in 54 Mbps for 30 seconds by using iperf at the network layer to both WiFi clients simultaneously, but data were transmitted according to the bit-rate selection algorithm in AP. The transmission power at AP is 11 dBm. In addition to the bit-rate selection algorithms used for the single WiFi client based scenarios, OHBR was also included. WiFi channel 8 was used.

4.5.4 Multi-Vehicular WiFi Network

The multi-vehicular WiFi network was a typical type of roadside vehicular WiFi networks and all the WiFi clients are mobiles as each client is embedded in a car. In our experiment two train based WiFi clients were used. This scenario is the main scenario in our experiments for studying the performance of bit-rate selection algorithms for roadside multi-vehicular WiFi networks.

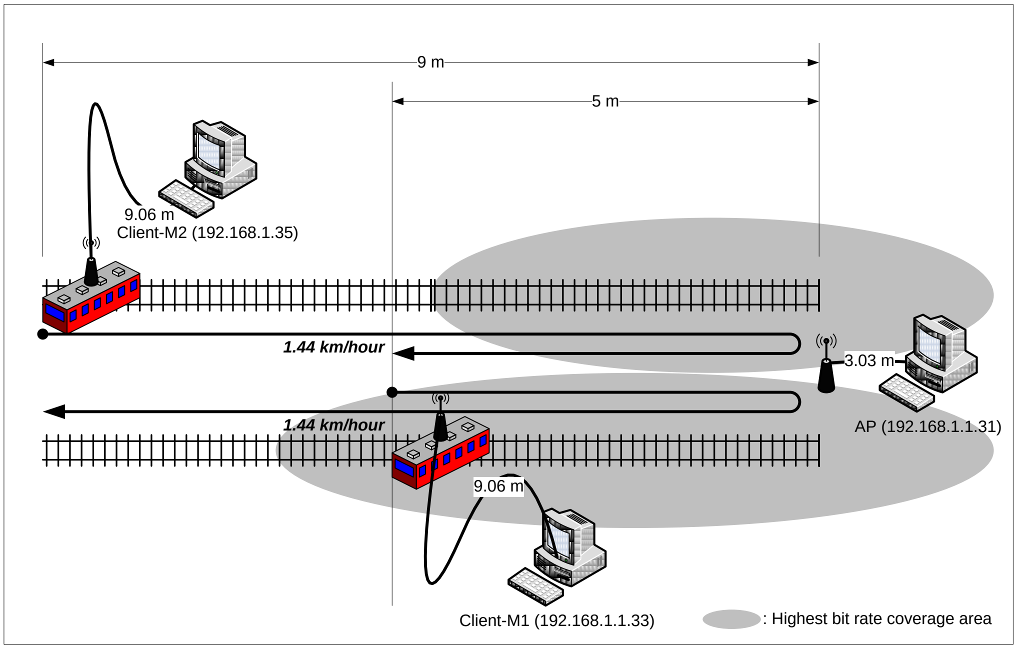


Figure 7: Multi-vehicular WiFi network testbed

This experiment testbed represents a multi-vehicular WiFi network that enables at least one vehicular WiFi client stays within the highest bit-rate coverage area and the AP is placed at the roadside.

In order to simulate a real multi-vehicular WiFi network, each train starts from different locations. One (M1) starts moving at the location of 5 meters apart from AP where it is in the highest bit-rate coverage area, but stops at the location of 9 meters apart from AP where is outside the highest bit-rate coverage area. This means that the client starts at the highest bit-rate coverage area, but leaves the coverage area. The other vehicle (M2) starts moving at the location of 9 meters apart from AP, but stops at the location of 5 meters apart from AP. This means, unlike M1, M2 starts outside the highest bit rate coverage area and enters and stops in the highest bit rate coverage area. Each vehicle moves for 30 seconds in 12 meters, so the speed is 1.44 km/hour.

Like the fixed-mobile WiFi network scenario, AP sent unicast UDP packets in 54 Mbps for 30 seconds by using iperf at the network layer to both WiFi clients simultaneously, but data was transmitted according to the bit-rate selection algorithm in AP. The transmission power at AP is 12 dBm. WiFi channel 8 was used.

4.6 Logging

For each WiFi station we monitored *ath1* (monitored network interface for Atheros) and captured the WiFi frames being transmitted from AP to WiFi client by using *tcpdump* (version 3.9.4). After completing an iteration of each experiment, all *tcpdump* files were collected and parsed. And then the following test results for a particular bit-rate selection algorithm were produced:

- Graph of performance attributes (e.g., throughput, bit-rate) per each bit-rate selection algorithm in each iteration.
- Timeline (200 milliseconds time unit) based transmission data and status such as bit-rate, throughput, etc.

Based on the test results, the performance comparison between each bit-rate selection algorithms on each test scenario (single-fixed WiFi network, single-vehicle WiFi network, fixed-mobile WiFi network, and multi-vehicle WiFi network) was easily observed.

4.7 Performance Metrics

The main transaction in roadside multi-vehicular WiFi networks is data download from AP to each vehicle. For example, when a WiFi enabled vehicle approaches a critical place such as Tourist Information Office, the driver or passengers in the vehicle may want to download useful and valuable information from the office. The office may also want to advertise something, such as tourism locations, to all the passing vehicles effectively. Therefore, our primary interesting transaction in roadside multi-vehicular WiFi networks is the data transfer from AP to WiFi client(s). We are interested in two performance metrics in roadside multi-vehicular WiFi networks from the perspective of throughput performance:

- Overall throughput: Total throughput of WiFi frame transmission from AP to all the WiFi clients. Maximizing overall throughput is very critical for roadside multi-vehicular WiFi networks. Therefore, this metric can be one of the attributes to indicate quality of the bit-rate selection algorithm for roadside multi-vehicular WiFi networks.

- Fairness: Individual throughput from AP to each WiFi client. It is also crucial to maximize individual throughput. In other words, AP wants to have the same individual throughputs across all the WiFi clients as greatly as possible in the long-term. In order to achieve fairness of individual throughput across all the vehicles, in addition to the packet scheduling, the bit-rate selection algorithm must be efficient to fit roadside multi-vehicular WiFi networks. Therefore, this metric can be used to evaluate quality of fairness for a bit-rate selection algorithm for roadside multi-vehicular WiFi networks.

Chapter 5

Evaluation

We evaluated a number of bit-rate selection algorithms (6 adaptive bit-rate selection algorithms and 10 fixed bit-rates) in four scenarios. We used 10 test data for each bit-rate selection algorithm in each WiFi network scenario: single-fixed (client based) WiFi network, single-vehicular (client based) WiFi network, fixed-vehicular (clients based) WiFi network and multi-vehicular (clients based) WiFi network.

As mentioned in Chapter 4, there were two performance metrics: 1) throughput of the entire network from the perspective of AP and 2) fairness of individual throughput between all the WiFi clients.

5.1 Performance Analysis in Scenarios

Prior to evaluating a number of bit-rate selection algorithms in the multiple clients based vehicular WiFi network, we measured it in the single client based WiFi network for several reasons.

Firstly, although the similar performance evaluations were already made from many prior researches, it is useful to confirm it in our testbed WiFi network for the single client based WiFi network so the result can be the basis used to compare with and verify our experimental performance results in the various vehicular WiFi network scenarios. Secondly, it also helps finding any characteristics and/or attributes that can affect the performance of the multi-client-based vehicular WiFi network, by comparing the performance results between the single client based WiFi network and the multiple clients based WiFi network.

There are two scenarios for the single client based WiFi network: single fixed WiFi network and single-vehicular WiFi network.

5.1.1 Single-Fixed WiFi Network

We evaluated the performance of the bit-rate selection algorithms in the single-fixed WiFi network based on 10 test results of data transmission from AP to the fixed WiFi client for 30 seconds per each bit-rate selection algorithm. The fixed WiFi client resides in the highest bit-rate coverage area. Table 4 depicts the throughputs of 10 tests for each bit-rate selection algorithm according to 95% CI Confidence Interval (CI) based on mean. In Table 4 some bit-rate selection methods show that the throughputs are higher than the amounts of the frames sent. During the experiments, we found a small probability of data losses at the monitoring WiFi interface *ath0*. However, unlike the data losses at the receiver, the sender does not retransmit the data losses in the monitor at the sender side. This phenomenon causes the frame amounts that are monitored at the sender side to be less than the throughputs. In comparing, the data losses in the monitor are smaller. We leave the results in our thesis to explain. Figure 8 also depicts the performance results of the bit-rate selection algorithms in the single-fixed WiFi network through the graphs.

Table 4: Performance of bit-rate selection algorithms in the single-fixed WiFi network

method	sender (AP)				receiver (fixed client)				error	
	95% CI		mean	R	95% CI		mean	R	rate	R
amrr	110231994	114446767	112339381	3	110280612	114553635	112417123	1	-0.07	13
onoe	106019471	108317428	107168450	6	106208946	108420893	107314920	6	-0.14	9
sample	94576171	95267904	94922037	8	95052217	95333101	95192659	8	-0.29	2
rraa	122188282	124028486	123108384	2	109573215	113707654	111640434	4	9.32	16
mdrs	128135181	129788825	128962003	1	105787764	113463781	109625773	5	15	17
1M	3392551	3412161	3402356	17	3395320	3414418	3404869	17	-0.07	12
2M	6615577	6754409	6684993	16	6620463	6759871	6690167	16	-0.08	11
5.5M	16683913	16951229	16817571	15	16710155	16973760	16841958	15	-0.15	8
11M	30313570	30988550	30651060	12	30329276	31022800	30676038	12	-0.08	10
6M	19524756	19821673	19673215	14	18681081	20098751	19389916	14	1.44	15
9M	28781115	29430211	29105663	13	28865645	29487568	29176607	13	-0.24	5
12M	37554192	37941161	37747677	11	37563032	37970158	37766595	11	-0.05	14
18M	54064698	54472553	54268626	10	54278937	54542065	54410501	10	-0.26	3
24M	68406991	69522925	68964958	9	68741684	69602959	69172321	9	-0.3	1
36M	94809831	95493015	95151423	7	94924360	95710445	95317402	7	-0.17	7
48M	110905923	112741785	111823854	5	111120602	113101753	112111177	3	-0.26	4
54M	110182486	114142738	112162612	4	110320247	114429458	112374853	2	-0.19	6

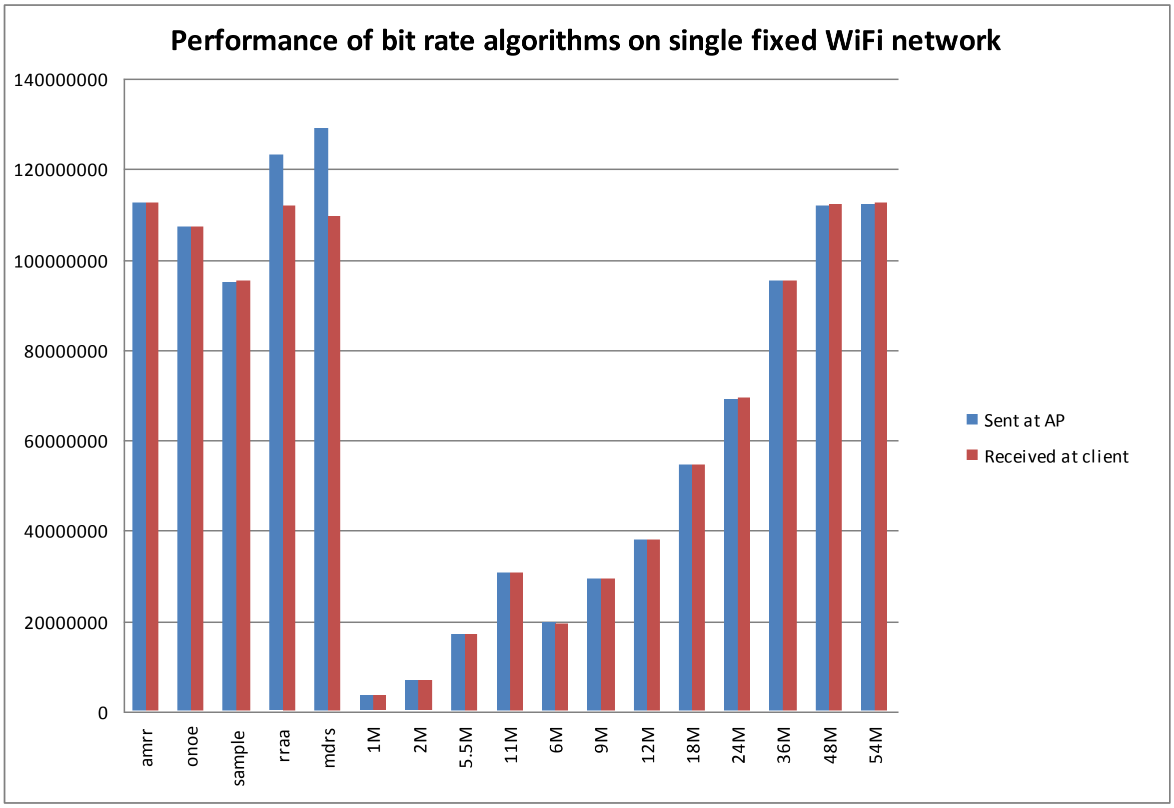


Figure 8: Performance of bit-rate selection algorithms in the single-fixed WiFi network

From the above result the following observations were made:

- AMRR (112.4 Mbytes) shows the best throughput among all the tested bit-rate selection algorithms. Other adaptive bit-rate selection algorithms, such as RRAA (i.e., 111.6 Mbytes), MDRS (109.6 Mbytes) and ONOE (107.3 Mbytes), also show good performance in terms of throughput. Their throughputs are in between the range of 54 Mbps and 36 Mbps fixed bit-rates.

- As the fixed WiFi client resides in the highest bit-rate coverage area, 54 Mbps fixed bit-rate shows the best throughput (112.3 Mbytes) among all the fixed bit-rates. 48 Mbps fixed bit-rate also shows good performance (112.1 Mbytes), which is approximately equal to that of the 54 Mbps fixed bit-rate.

- Relatively, MDRS shows good performance compared to other bit-rate selection algorithms. However, it has a high error rate (15%) although it has the highest throughput at the sender (128.96 Mbytes) with a factor of 1.05, 1.15 and 1.15 higher than RRAA, AMRR and the fixed bit-rate with 54 Mbps, respectively. According to the diagrams in Section 0 and 0, we can see that MDRS seems to over-estimate the transmission rate and have significant data losses. The range of data-transmission based on the timeline on the datagram in Section 0 is in between 400 Kbytes(/0.2 seconds) and 500 Kbytes, while the range of data reception in Section 0 is in between 300 Kbytes and 400 Kbytes. RRAA is similar with MDRS, but with a lesser over-estimation than MDRS. It has relatively good performance at the sender, but it has a high error rate (9.3%).

- The reason other bit-rate selection algorithms do not produce high error rate is that the lost frames are retransmitted until reaching the maximum retransmission times. However, MDRS and RRAA do not retransmit the loss packets.

5.1.2 Single-Vehicular WiFi Client

We also evaluated the performance of the bit-rate selection algorithms in the single-vehicular WiFi network. We performed 10 tests per each bit-rate selection algorithm with data transmission from AP to the vehicular WiFi client for 30 seconds. The vehicular WiFi client starts from a poor performance coverage area (about 10 Mbps as the suitable transmission rate), and then enters the highest bit-rate coverage area at the middle of the train railroad. Table 5 depicts throughput of 10 tests for each bit-rate selection method with 95% CI based on the mean. Figure 9 also shows the performance result for each bit-rate selection algorithm in the single-vehicular WiFi network, based on the graphs. In this experiment, we made the following observations:

- Most of the adaptive bit-rate selection algorithms (RRAA, ONOE, AMRR and SAMPLE) show good performance of throughput. Especially, RRAA has the highest performance result (80.99 Mbytes). There is no noticeable performance difference between the long-term variations focused and the short-term variations focused adaptive bit-rate selection algorithms (e.g., ONOE vs. RRAA or ONOE vs. AMRR). Even the result of ONOE is better than that of AMRR with a factor of 1.009. In terms of error rate, RRAA has a high error rate of 20%, while AMRR and ONOE have almost 0% error rate. Therefore, given the performance result of throughput and error rate, ONOE and AMRR may be considered as an effective adaptive bit-rate selection algorithms for the single-vehicular WiFi network.

- 36 Mbps fixed bit-rate performed well, even compared to the adaptive bit-rate selection algorithms. It has a very good performance result which is almost the same as the one of

RRAA with a performance difference factor of 0.984. In addition to the good performance, its error rate is minimal (0.54 %). Therefore, given the performance result based on throughput and error rate, 36 Mbps fixed bit-rate can also be considered as an effective transmission-rate handling method for the single-vehicular WiFi network. There is also another advantage that its implementation and operation is much simpler than that of any adaptive bit-rate selection algorithms.

- MDRS didn’t perform well, although the throughput at the sender was the best (113.5 Mbytes). According to the diagrams of MDRS in Section 0 and 0, we can see the significant data loss. Therefore, MDRS seemed to over-estimate, which resulted in an exceeded high error rate (50.4 %). However, unlike the performance result in the single-vehicular WiFi network, MDRS shows good performance in the multiple WiFi clients based vehicular network, such as the fixed-mobile WiFi network and the multi-vehicular WiFi network. We leave the investigation on the reason for the high error rate in the single-vehicular WiFi network for future research.

Table 5: Performance of bit-rate selection algorithms in the single-vehicular WiFi network

method	sender (AP)				receiver (mobile client)				error	
	95% CI		mean	R	95% CI		mean	R	Rate	R
amrr	75775758	81394466	78585112	5	75693142	81397271	78545206	4	0.05	11
onoe	76244656	82149943	79197300	4	76307963	82154625	79231294	3	-0.04	7
sample	74336419	81862760	78099589	6	73995497	81369498	77682498	5	0.53	12
rraa	99213314	103638934	101426124	2	77859410	84113723	80986567	1	20.2	16
mdrs	109186905	117871436	113529171	1	52273269	60297418	56285344	8	50.4	17
1M	3316813	3382666	3349739	17	3318053	3383790	3350922	17	-0.04	8
2M	6418721	6634975	6526848	16	6421276	6640992	6531134	16	-0.07	6
5.5M	16385807	16498215	16442011	15	16420992	16534515	16472753	15	-0.19	2
11M	29367569	29916194	29641881	12	29378610	29948901	29663756	12	-0.07	5
6M	18263568	18927642	18595605	14	18245224	18945986	18595605	14	0	10
9M	27088902	27840081	27464492	13	27169930	27867834	27518882	13	-0.2	1
12M	35168704	36332797	35750751	11	35207730	36370923	35789327	11	-0.11	3
18M	50516340	51798505	51157423	10	50516260	51828146	51172203	9	-0.03	9
24M	62341384	65651938	63996661	8	62413920	65681384	64047652	7	-0.08	4
36M	78422021	81891318	80156670	3	77815723	81638603	79727163	2	0.54	13
48M	62376427	73180412	67778420	7	59273035	70655285	64964160	6	4.15	14
54M	53947431	57409819	55678625	9	49046701	52742272	50894487	10	8.59	15

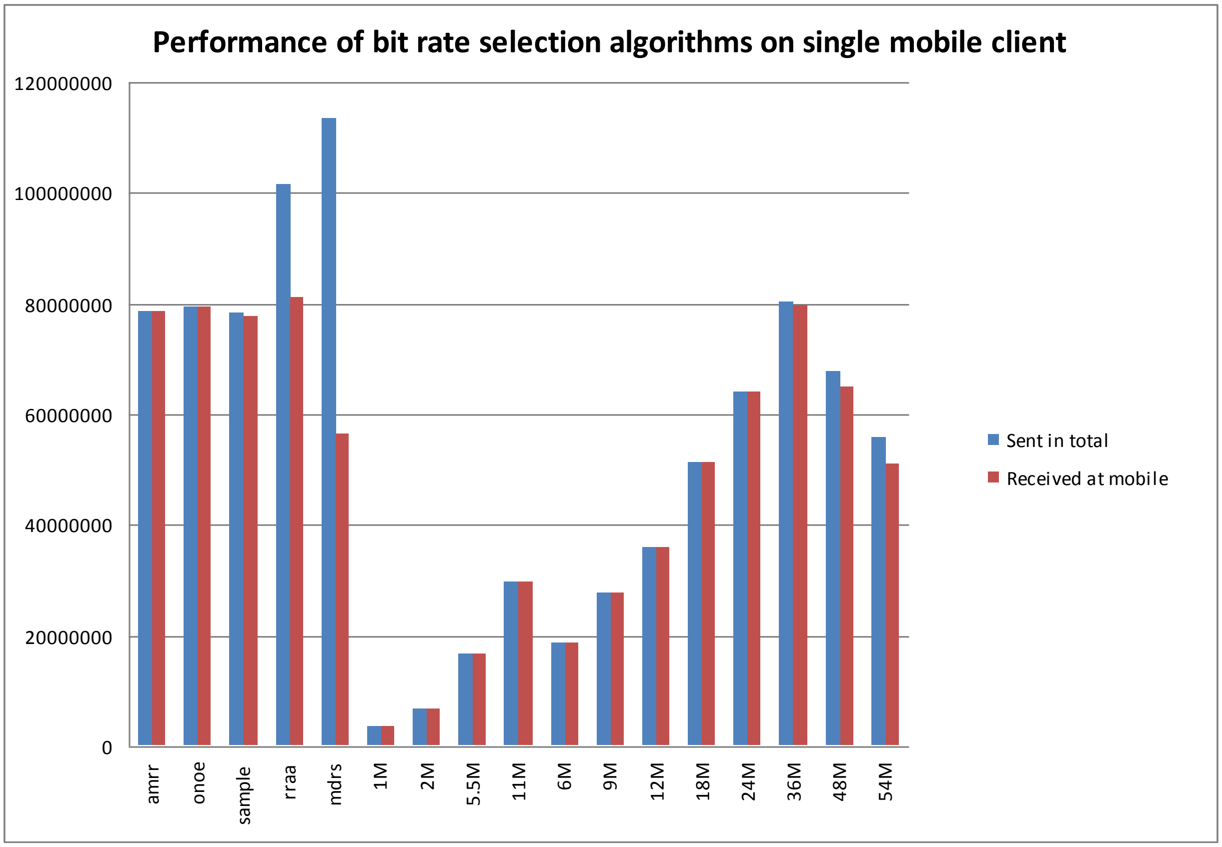


Figure 9: Performance of bit-rate selection algorithms in single-vehicular WiFi network

5.1.3 Fixed-Mobile WiFi Network

We performed our experiments in two scenarios to evaluate the performance of a number of bit-rate selection algorithms in the multi-client-based vehicular WiFi network. The first scenario is for the fixed-mobile WiFi network. The fixed-mobile WiFi network means a multiple clients based WiFi network that consists of fixed WiFi client(s) and vehicular WiFi client(s). The other scenario is for the multi-vehicular WiFi network that only has vehicular WiFi client(s). This scenario is addressed in the next section (5.1.4). In the scenarios of the multi-client-based vehicular WiFi network, we also evaluated OHBR. As mentioned in Chapter 3, OHBR is an opportunistic fixed highest bit-rate-based transmission-rate handling method.

In our experiment for the fixed-mobile WiFi network, the fixed WiFi client is placed at the roadside in the middle of a toy train railroad. And, like the scenario for the single-vehicular WiFi client in the single-vehicular WiFi network, the vehicular WiFi client starts from a poor performance coverage area, and then moves into the highest bit-rate coverage area where it starts at the middle of the railroad. We performed 10 tests per each bit-rate selection algorithm with data transmission from AP to both WiFi clients simultaneously for 30 seconds. Table 6 depicts throughputs of 10 tests for each bit-rate selection algorithm according to 95% CI based on mean. Table 7 depicts the performance result of 10 tests for each bit-rate selection algorithm with the means from 95% CI, the error rates and the fairness results across the WiFi clients. Figure 10 also depicts the performance result for each bit-rate selection algorithm through the graphs.

Table 6: Throughput of bit-rate selection algorithms in the fixed-mobile WiFi network

	sender (AP)				receiver (fixed client)				receiver (mobile client)			
method	95% CI		mean	R	95% CI		mean	R	95% CI		mean	R
amrr	83774330	94467149	89120740	7	49003066	55111984	52057525	6	34492787	39748040	37120413	4
onoe	76153624	86135506	81144565	9	47989226	53061929	50525578	8	27572766	33916172	30744469	8
sample	85802471	93316349	89559410	6	51790354	57207121	54498737	5	33572249	36621518	35096884	5
rraa	105383613	111029467	108206540	3	49620945	53239578	51430262	7	40924642	43739041	42331841	1
mdrs	121572941	124292655	122932798	1	56449681	60269457	58359569	2	32089046	34803165	33446105	6
1M	3300050	3377850	3338950	18	1654515	1729810	1692162	18	1597085	1700333	1648709	18
2M	6528246	6572450	6550348	17	3185815	3314724	3250270	17	3254275	3352385	3303330	17
5.5M	16456152	16659621	16557886	16	8316374	8459813	8388093	16	8100631	8248414	8174522	16
11M	29966895	30272246	30119571	13	15148922	15313544	15231233	13	14821024	15007972	14914498	13
6M	17883562	18592296	18237929	15	9302251	9672905	9487578	15	8396188	9132892	8764540	15
9M	26383720	27335964	26859842	14	13805533	14279631	14042582	14	12475131	13156936	12816034	14
12M	34641223	35229158	34935190	12	18015027	18577001	18296014	12	16429462	16907732	16668597	12
18M	49802300	51250038	50526169	11	25842755	26801832	26322293	11	23916399	24521504	24218951	10
24M	61486787	64583066	63034926	10	32782669	34081165	33431917	10	28611848	30690537	29651193	9
36M	81964515	85680591	83822553	8	44668189	46358875	45513532	9	36793482	38959634	37876558	2
48M	91348610	95933499	93641055	4	53752039	56193129	54972584	4	35980824	38715818	37348321	3
54M	89547228	93082729	91314978	5	56126217	58751924	57439071	3	30360999	33255669	31808334	7
OHBR	108235241	118679734	113457488	2	91238238	1.01E+08	96212627	1	16662688	17737762	17200225	11

Table 7: Performance of bit-rate selection algorithms in the fixed-mobile WiFi network

	Sent		Total receivered		error		fairness			
method	mean	R	total	R	rate	R	fixed	mobil	F-V	R
amrr	89120740	7	89177938	7	-0.06	6	0.58	0.42	0.17	12
onoe	81144565	9	81270047	9	-0.15	1	0.62	0.38	0.24	15
sample	89559410	6	89595621	5	-0.04	9	0.61	0.39	0.22	14
rraa	108206540	3	93762103	2	13.3	17	0.55	0.45	0.1	11
mdrs	122932798	1	91805674	4	25.3	18	0.64	0.36	0.27	16
1M	3338950	18	3340871	18	-0.06	7	0.51	0.49	0.01	4
2M	6550348	17	6553600	17	-0.05	8	0.5	0.5	0.01	1
5.5M	16557886	16	16562615	16	-0.03	11	0.51	0.49	0.01	3
11M	30119571	13	30145731	13	-0.09	2	0.51	0.49	0.01	2
6M	18237929	15	18252118	15	-0.08	4	0.52	0.48	0.04	5
9M	26859842	14	26858616	14	0	12	0.52	0.48	0.05	7
12M	34935190	12	34964611	12	-0.08	3	0.52	0.48	0.05	8
18M	50526169	11	50541244	11	-0.03	10	0.52	0.48	0.04	6
24M	63034926	10	63083110	10	-0.08	5	0.53	0.47	0.06	9
36M	83822553	8	83390090	8	0.52	14	0.55	0.45	0.09	10
48M	93641055	4	92320905	3	1.41	15	0.6	0.4	0.19	13
54M	91314978	5	89247405	6	2.26	16	0.64	0.36	0.29	17
OHBR	113457488	2	113412852	1	0.04	13	0.85	0.15	0.7	18

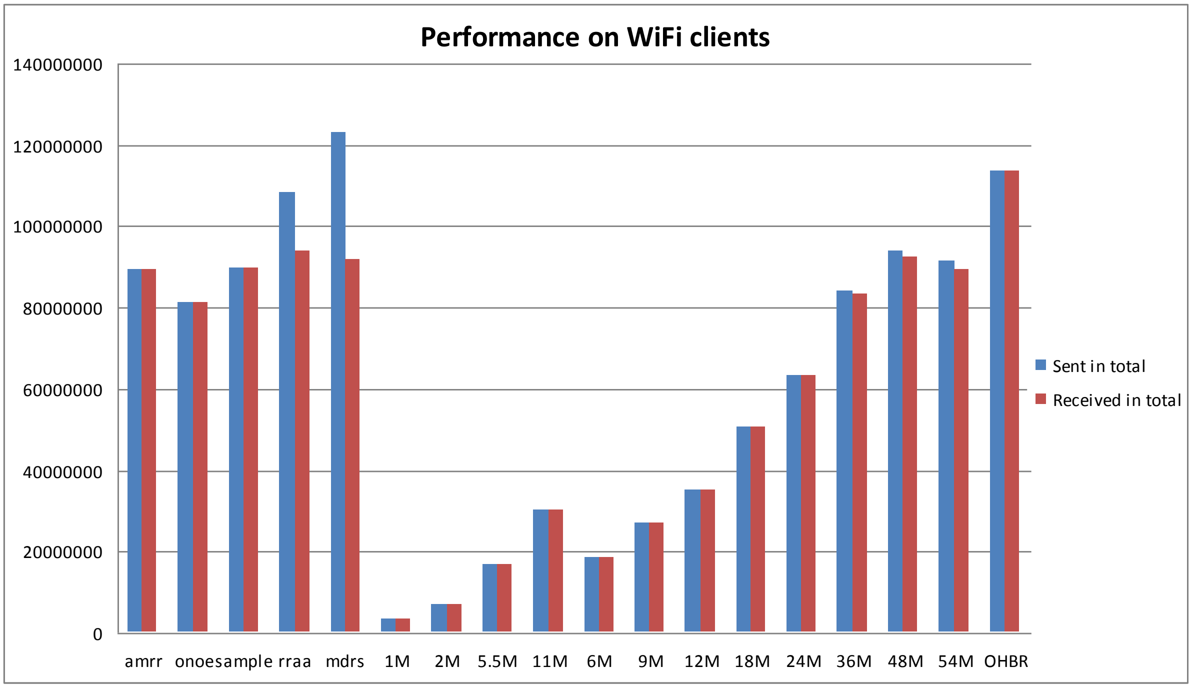


Figure 10: Performance of bit-rate selection algorithms in the fixed-mobile WiFi network

From the above test result, the following observations were made:

- Most of the adaptive bit-rate selection algorithms (RRAA, MDRS, SAMPLE and AMRR) performed relatively well. Especially, RRAA has best performed among the bit-rate selection algorithms except for OHBR. However, MDRS and RRAA had very high loss rates (25.3%, 13.3% respectively), while AMRR and SAMPLE had almost 0% loss rates. MDRS and RRAA may over-estimate the transmission rate, so the bit-rate selection accuracy is relatively lower. Some losses from RRAA may be expected since the algorithm is based on the short-term loss rate.

- Some fixed bit-rates, such as 48 Mbps and 54 Mbps, show relatively good performance compared to the adaptive bit-rate selection algorithms. One of the reasons may be that the fixed WiFi client is placed in the highest bit-rate coverage area. This means that if a certain WiFi network has a sufficient highest bit-rate coverage area, some fixed bit-rates such as 48 Mbps and 54 Mbps, would perform well. For the fixed WiFi client, the order of good performers is 54 Mbps, 48 Mbps and 36 Mbps respectively, whereas 36 Mbps, 48 Mbps and 54 Mbps for the vehicular WiFi client. And the error rates for the vehicular WiFi client in the order of 36 Mbps, 48 Mbps and 54 Mbps are 0.52%, 1.41% and 2.26%. Since 48 Mbps has a relatively good performance compared to the adaptive bit-rate selection algorithms and low loss rate, it can be considered as an effective transmission-rate handling method for the fixed-mobile WiFi network.

- OHBR outperformed among all the evaluated algorithms as it sent data with the highest bit-rate only to the WiFi clients placed in the highest bit-rate coverage area. It also has low error rate. And another advantage is that it is much simpler to implement and operate than any adaptive bit-rate selection algorithms as it is also fixed bit-rate based. Therefore, OHBR is a very effective transmission-rate handling method in the fixed-mobile WiFi network.

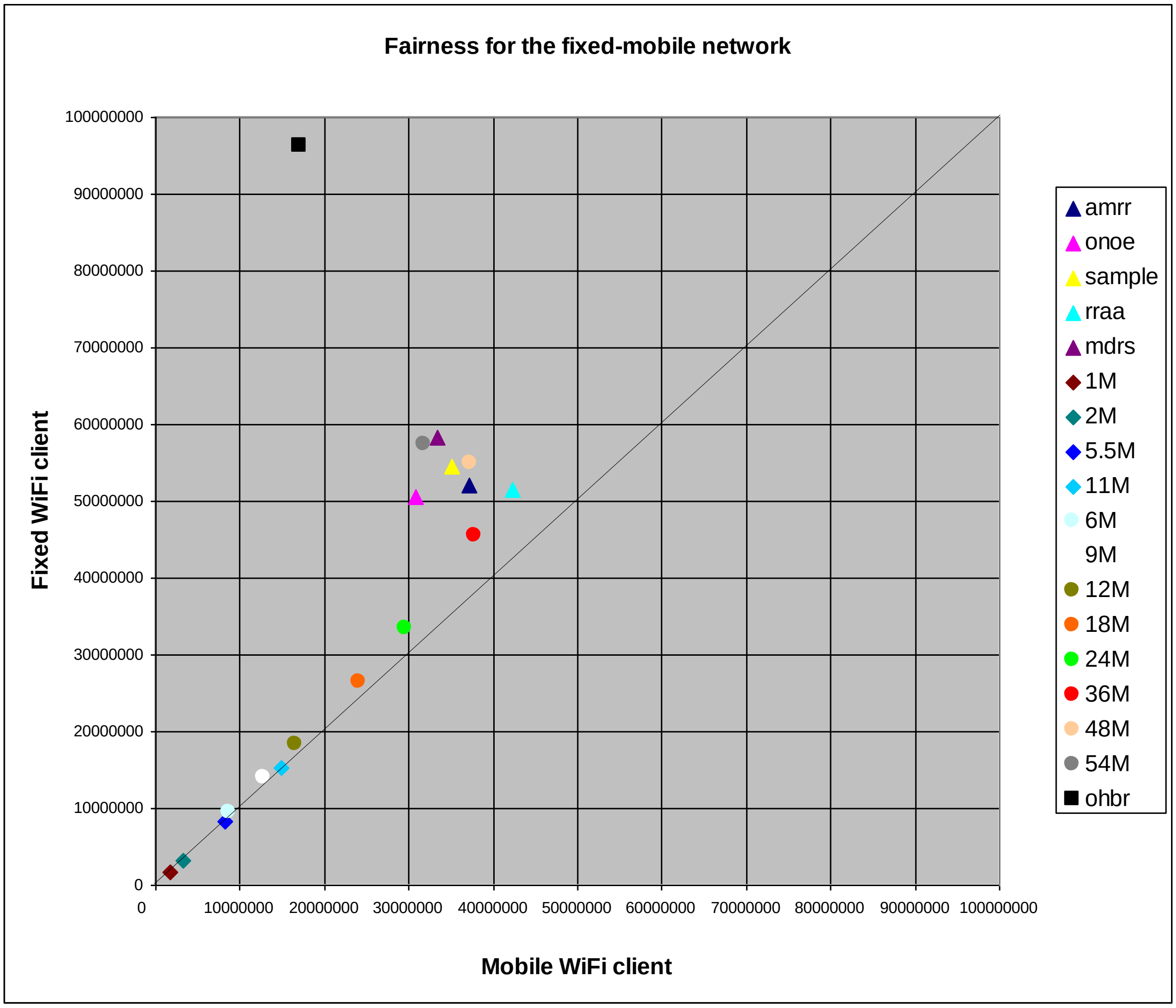


Figure 11: Fairness of bit-rate selection algorithms in the fixed-mobile WiFi network

In this thesis, we also made the following observations for fairness focusing on the individual throughput of each mobile WiFi client in the fixed-mobile WiFi network:

- In the above diagram, it is clear that the fixed bit-rates for 802.11b (1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps) performed well in the fixed-mobile WiFi network in terms of fairness, compared to other fixed bit-rates supported by 802.11g and the adaptive bit-rate selection algorithms.
- RRAA shows good fairness. Especially, it is the best among the adaptive bit-rate selection algorithms. Therefore, given the performance result of throughput and fairness, RRAA seems to be the best effective bit-rate selection algorithm in the fixed-mobile WiFi network.
- 36 Mbps fixed bit-rate also shows relatively good fairness. Therefore, given the performance result of throughput and fairness, the fixed bit-rate is the best effective bit-rate decision method among the fixed bit-rates.
- OHBR shows the worst fairness compared to all other bit-rate selection algorithms. The reason is that OHBR continues sending data to the fixed WiFi client as it resides in the highest bit-rate coverage area. This fact implicitly indicates that OHBR needs an effective fairness mechanism to limit data transmission to the fixed WiFi client in the highest bit-rate coverage area within a certain period in order to improve fairness, while maintaining the best throughput for the entire network. Therefore, the time-based fairness may be an effective method to improve fairness, while maintaining the best throughput of the WiFi network.

5.1.4 Multi-Vehicular WiFi Network

For evaluating the performance of the bit-rate selection algorithms in the multi-vehicular WiFi network, we used two toy train based vehicular WiFi clients. In order to make our testbed similar to the real multi-vehicular WiFi network, both WiFi clients move in the different WiFi channel conditions. One (M2) starts from the same position where the vehicular WiFi client does in the single-vehicular WiFi network, but it terminates at the middle of the railroad on the way back from AP after changing the direction. This means that M2 starts from the poor performance coverage area, and then moves into and terminates in the highest bit-rate coverage area. Meanwhile, the other train (M1) starts from the middle of the railroad, but terminates where the other train (M1) starts. Therefore, unlike M2, M1 starts from the highest bit-rate coverage area, but terminates at the poor performance coverage area. Like the scenario of the fixed-mobile WiFi network, OHBR was also evaluated.

We performed 10 tests per each bit-rate selection algorithm with data transmission from AP to both WiFi clients for 30 seconds. As previously mentioned, in order to make it similar to the real multi-vehicular WiFi network, the test bed was configured with only 1 vehicle (M2) in the highest bit-rate during the first 10 seconds, then both vehicles (M1 and M2) in the highest bit-rate coverage for the next 10 seconds, and then 1 vehicle (M1) in the highest bit-rate coverage area for the last 10 seconds. Table 8 depicts throughput of 10 tests for each bit-rate selection method with 95% CI based on mean. Table 9 depicts the performance result of 10 tests for each bit-rate selection algorithm with the means from 95% CI, the error rates and the fairness results. Figure 12 also depicts performance result for each bit-rate selection algorithm.

Table 8: Throughput of bit-rate selection algorithms in the multi-vehicular WiFi network

method	sender (AP)				receiver (1st mobile client)				receiver (2nd mobile client)			
	95% CI		mean	R	95% CI		mean	R	95% CI		mean	R
amrr	65684301	76419487	71051894	8	43266261	47098067	45182164	5	20687457	30605350	25646404	8
onoe	57307338	60590062	58948700	9	42752752	45870481	44311616	7	14052677	14802317	14427497	12
sample	68880303	75420088	72150196	7	42755361	47367758	45061560	6	25222315	28827553	27024934	7
rraa	87746307	91332607	89539457	3	38748091	41269351	40008721	9	30371340	32864890	31618115	5
mdrs	12215617	123755380	122955998	1	47484090	50970811	49227450	3	34494486	40569187	37531836	2
1M	3334056	3397643	3365849	18	1644421	1715665	1680043	18	1630415	1743464	1686939	18
2M	6549911	6644490	6597201	17	3217702	3360876	3289289	17	3250833	3367060	3308946	17
5.5M	15891853	16613210	16252531	15	7758999	8423737	8091368	16	7830375	8465877	8148126	15
11M	28705827	30629074	29667451	12	13608455	15653285	14630870	13	14780778	15317214	15048996	11
6M	14289316	17290745	15790031	16	7925485	8963030	8444257	15	5983104	8221658	7102381	16
9M	18676873	22215261	20446067	14	10262832	11817010	11039921	14	7654491	10175510	8915000	14
12M	26997378	28651391	27824385	13	15914904	16652548	16283726	12	10357876	11524505	10941191	13
18M	39121352	44658782	41890067	11	23598357	25110907	24354632	11	14552559	19066029	16809294	10
24M	50498721	57346209	53922465	10	31249987	33084397	32167192	10	17803325	23809765	20806545	9
36M	69380312	76664711	73022511	6	43402339	44686461	44044400	8	24151033	31065865	27608449	6
48M	79932378	88211405	84071892	4	47957135	50688772	49322953	2	28745380	36124040	32434710	4
54M	79772609	85962286	82868947	5	43828387	48776590	46302488	4	30945042	36577388	33761215	3
OHBR	97833492	105230110	101531801	2	52155085	53432034	52793559	1	44301445	51086310	47693878	1

Table 9: Performance of bit-rate selection algorithms in the multi-vehicular WiFi network

	Sent		Total received		error rate		fairness			
method	mean	R	mean	R	rate	R	fixed	mobile	F-V	R
amrr	71051894	8	70828568	8	0.314	6	0.64	0.36	0.28	17
onoe	58948700	9	58739113	9	0.356	7	0.75	0.25	0.51	18
sample	72150196	7	72086494	5	0.088	5	0.63	0.37	0.25	16
rraa	89539457	3	71626836	7	20.01	17	0.56	0.44	0.12	8
mdrs	122955998	1	86759286	2	29.44	18	0.57	0.43	0.13	9
1M	3365849	18	3366982	18	-0.03	2	0.5	0.5	0	1
2M	6597201	17	6598235	17	-0.02	3	0.5	0.5	0	2
5.5M	16252531	15	16239494	15	0.08	4	0.5	0.5	0	3
11M	29667451	12	29679866	12	-0.04	1	0.49	0.51	0.01	4
6M	15790031	16	15546638	16	1.541	9	0.54	0.46	0.09	6
9M	20446067	14	19954921	14	2.402	14	0.55	0.45	0.11	7
12M	27824385	13	27224917	13	2.154	13	0.6	0.4	0.2	12
18M	41890067	11	41163926	11	1.733	10	0.59	0.41	0.18	11
24M	53922465	10	52973737	10	1.759	11	0.61	0.39	0.21	14
36M	73022511	6	71652849	6	1.876	12	0.61	0.39	0.23	15
48M	84071892	4	81757663	3	2.753	15	0.6	0.4	0.21	13
54M	82868947	5	80063703	4	3.385	16	0.58	0.42	0.16	10
OHBR	101531801	2	100487437	1	1.029	8	0.53	0.47	0.05	5

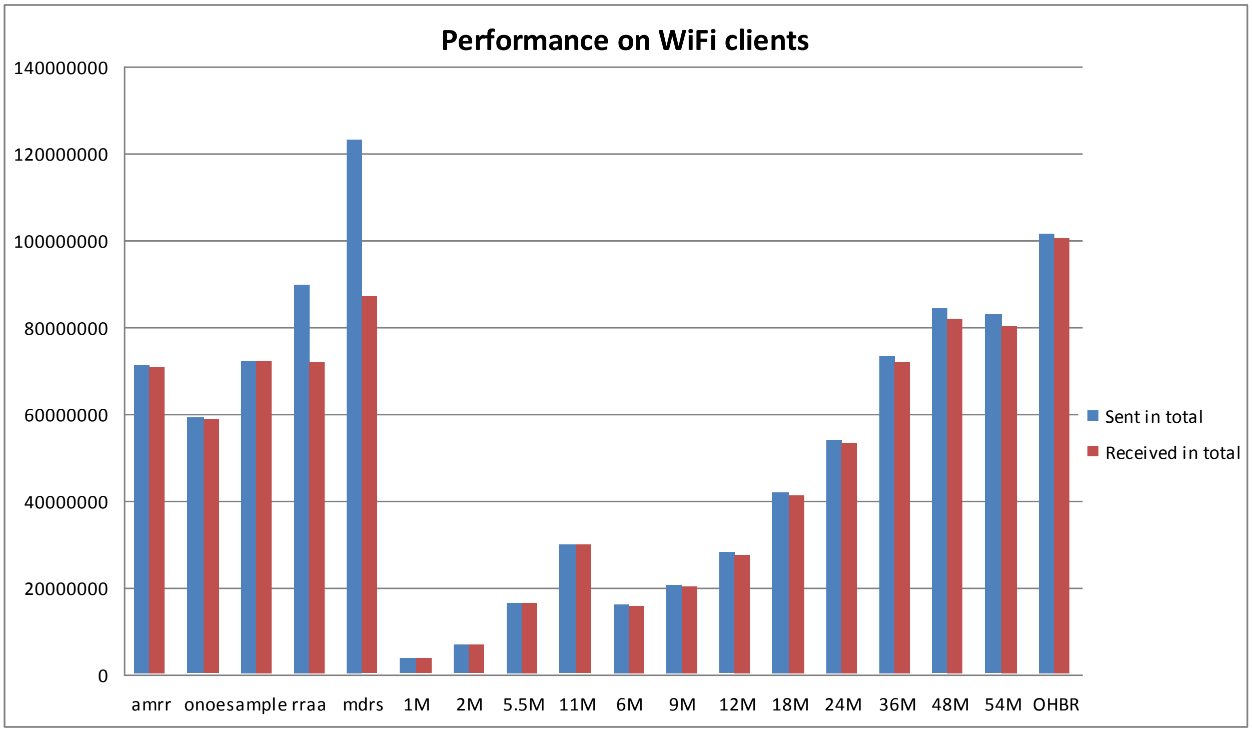


Figure 12: Performance of bit-rate selection algorithms in multi-vehicular WiFi network

In this experiment, the following observations were made:

- 48 Mbps and 54 Mbps fixed bit-rates relatively performed well compared to the adaptive bit-rate selection algorithms. Especially, like the scenario for the fixed-mobile WiFi network, 48 Mbps shows the very good performance result. It performed at a factor of 0.814, 0.942, 1.021 and 1.141 different from OHBR, MDRS, 54 Mbps and RRAA, respectively. It shows a certain degree of error rate (3.753 %). Along with the additional benefit of simplicity, given the performance result of throughput and the error rates, 48 Mbps fixed bit-rate seems to be an effective bit-rate selection method in the multi-vehicular WiFi network.

- Relatively, the adaptive bit-rate selection algorithms also performed well in the multi-vehicular WiFi network. Especially, MDRS shows the best performance result among all the bit-rate selection algorithms except OHBR. It shows the performance difference with a factor of 0.863, 1.204 and 1.211 from OHBR, SAMPLE and RRAA, respectively. However, it has a high loss rate (29.44%). RRAA also has a high loss rate (20.01%). This means that MDRS and RRAA overestimate the bit-rate similar in other scenarios.

- Like the scenario for the fixed-mobile vehicular WiFi network, OHBR shows the best performance among all the bit-rate selection algorithms. It has significant performance difference with a factor of 1.158, 1.229 and 1.255 from MDRS, 48 Mbps and 54 Mbps, respectively. It also has a relatively low loss rate (1.029%) and shows a good fairness result between the vehicular WiFi clients. Therefore, OHBR should be considered as a highly effective transmission-rate handling method in the multi-vehicular WiFi network.

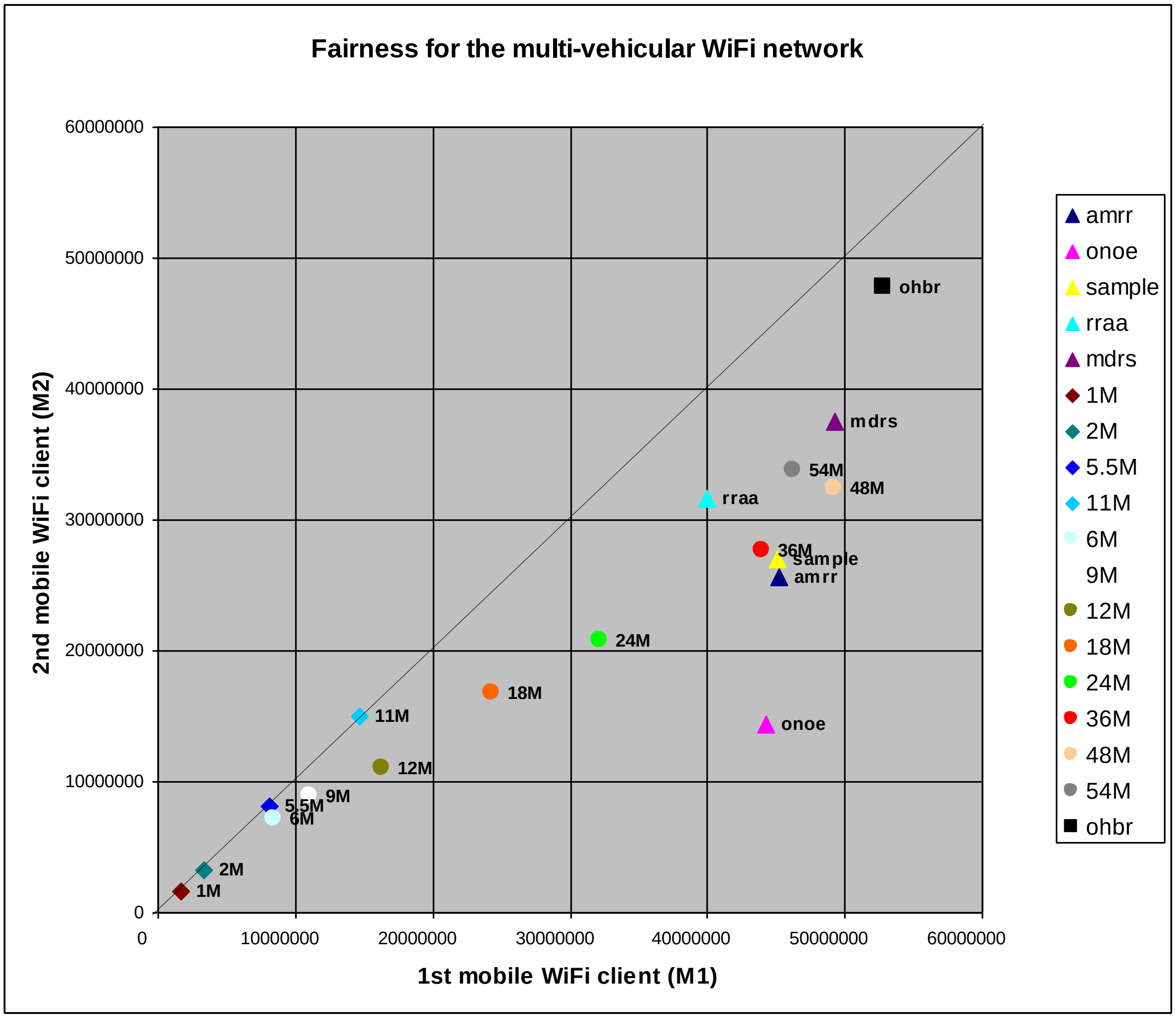


Figure 13: Fairness of bit-rate selection algorithms in the multi-vehicular WiFi network

We also made the following observations for fairness in the multi-vehicular WiFi network:

- In the above diagram, like the scenario for the fixed-mobile WiFi network, it is clear that all the fixed bit-rates supported by 802.11b show excellent fairness results as compared to other fixed bit-rates supported by 802.11g and the adaptive bit-rate selection algorithms. This implies that 802.11 wireless technologies seem to be a critical factor that determines and affects fairness in multi-vehicular WiFi networks. In our experiment for multi-vehicular WiFi networks, M1 had better throughputs and bigger highest bit-rate coverage area as compared to M1. However, according to the above diagram, 802.11b does not seem to be affected by this characteristic, but the fixed bit-rates supported by 802.11g had higher throughput in M1 than M2. Therefore, 802.11g seems to be affected by this circumstance in the multi-vehicular WiFi network in terms of fairness. The implication may not be restricted within the multi-vehicular WiFi network. It could be a generic or broad factor that affects any WiFi network.

- According to the above diagram, RRAA and MDRS seem to be fair compared to the bit-rate selection algorithms, especially for the adaptive bit-rate selection algorithms.
- ONOE had the worst fairness among all the bit-rate selection algorithms. The long-term variation based approach or the implementation of ONOE seems to affect fairness.
- Unlike the scenario for the fixed-mobile WiFi network, OHBR shows the best fairness. It sends almost equal amount of data to each client with the fixed highest bit-rate. The reason would be that the pattern of staying in the multi-vehicular WiFi network for each vehicular WiFi client is almost identical in terms of mobility and signal strength, etc.

5.2 Performance Analysis in Bit-Rate Selection Algorithms

5.2.1 Fixed Bit-Rates

In overall, higher fixed bit-rates such as 36 Mbps, 48 Mbps and 54 Mbps, performed well in 4 scenarios.

Obviously, they performed well in the single-fixed WiFi network since in our experiment the fixed WiFi client resides in the highest bit-rate coverage area. 54 Mbps fixed bit-rate must be the best, compared to any other bit-rate selection algorithms including the adaptive bit-rate selection algorithms. 48 Mbps fixed bit-rate also shows good performance result. It performed with a factor of 0.998, slightly lower than 54 Mbps fixed bit-rate. 36 Mbps fixed bit-rate performed with a factor of 0.85 lower than 48 Mbps and its performance was also lower as compared to the adaptive bit-rate selection algorithms (a factor of 0.848, 0.85, 0.87, 0.888 and 1.001 from AMRR, SAMPLE, RRAA, ONOE and MDRS respectively). In the single-vehicular WiFi network, both fixed bit-rates didn’t perform well as compared to other bit-rate selection algorithms, because the highest bit-rate coverage area is shrunk.

We found that higher fixed bit-rates such as 36 Mbps, 48 Mbps and 54 Mbps performed well in the roadside vehicular WiFi network. 48 Mbps and 54 Mbps fixed bit-rates performed well in the fixed-mobile WiFi network and the multi-vehicular WiFi network. In the fixed-mobile WiFi network, 48 Mbps performed with a factor of 0.98 lower than RRAA, but a factor of 1.006 higher than MDRS. 54

Mbps has the performance difference with a factor of 0.97, 0.996, 1.0 and 1.098 from MDRS, SAMPLE, AMRR and ONOE, respectively. In the multi-vehicular WiFi network, 48 Mbps has a performance difference with a factor of 0.94 and 1.134 from MDRS and SAMPLE, respectively. 54 Mbps performed a factor of 0.979 lower than 48 Mbps.

According to the above experimental results and the assumption that each vehicular WiFi client enters and stays in the highest bit-rate coverage area significantly in a roadside vehicular WiFi network, higher fixed bit-rates may perform well in vehicular WiFi networks in terms of throughput. Another advantage is that a fixed bit rate enables the result of fairness for DCF to be equal to the result of the time fairness, so it provides a good result of fairness. In addition, fixed bit-rate is much simpler than any adaptive bit-rate selection algorithms. Therefore, it is considered that a higher fixed bit-rate may be an effective bit-rate decision method in roadside vehicular WiFi networks. We confirmed that 48 Mbps fixed bit-rate was a very effective bit-rate decision method for vehicular WiFi networks.

According to our experiments, 54 Mbps is relatively inconsistent in our vehicular WiFi network scenarios (e.g., single-vehicular WiFi network, fixed-mobile WiFi network and multi-vehicular WiFi network). The reason seems to be significant packet losses at outside of the highest bit-rate coverage area. This means that efficiency for 54 Mbps in roadside vehicular WiFi networks would depend on the size of the highest bit-rate coverage area. We can consider two approaches to improve the performance with 54 Mbps fixed bit-rate. One is to increase the size of the highest bit-rate coverage area in the network, and the other approach is to reduce the error rate outside of the highest bit-rate coverage area. To increase the size of the highest bit-rate coverage area is the issue for network deployment and management, so there is not much area to research to improve the performance. However for the second approach, in order to reduce the error rate, we may find some good methods. One way is to drop the time spending of data transmission during out of the highest bit-rate coverage area. Instead, the time can be used for other WiFi clients who stay in highest bit-rate coverage area. This idea implicitly indicates that OHBR would be an effective bit-rate decision algorithm since it always sends data only to the WiFi clients who reside in the highest bit-rate coverage area so no significant data losses occur.

During our experiments, we found an interesting fact that the fixed bit-rates supported by 802.11b (1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps) performed extremely well regardless of any scenarios in multiple WiFi clients based WiFi network, as compared to other bit-rate selection algorithms including the fixed bit-rates supported by 802.11g, in terms of fairness. It would be worthy to investigate the reason that 802.11b has significantly better fairness than 802.11g in multiple clients based WiFi networks. We leave the investigation for future research.

5.2.2 AMRR

AMRR addresses not only the long-term variations based on probing and BEB but also the short-term variations by simplifying the values of the bit-rate/transmission count pairs in the MADWiFi driver. In general the performance of AMRR was consistent across various scenarios in the fixed WiFi network and for the vehicular WiFi network.

In the fixed WiFi network, the performance of AMRR is the best among all the bit-rate selection algorithms without any noticeable loss rate (almost 0%). It is almost the same as that of 54 Mbps, 48 Mbps and RRAA with a factor of almost 1.000, 1.003 and 1.006, respectively.

In the vehicular WiFi network, AMRR also shows good performance compared to other bit-rate selection algorithms. In the single-vehicular WiFi network, it performed with a factor of 0.917 lower than RRAA. In the fixed-mobile WiFi network, it performed with a factor of 0.786, 0.951, 0.971 and 0.995 lower than OHBR, RRAA, MDRS and SAMPLE, respectively. In the multi-vehicular WiFi network, it performed with a factor of 0.705, 0.816, 0.983 and 0.989 lower than OHBR, MDRS, SAMPLE and RRAA, respectively. AMRR shows relatively slower progress in bit-rate change at the 2nd WiFi client, which started from the outside of the highest bit-rate coverage area. This shows that the 2nd WiFi client does not have good performance. As a result, AMRR did not perform well in terms of fairness, as compared to the other bit-rate selection algorithms. It shows the second lowest fairness result.

5.2.3 ONOE

ONOE is the long-term statistics based bit-rate selection algorithm. According to our test results in Section 5.1, ONOE had the lowest performance result overall among the adaptive bit-rate selection algorithms, especially in the multiple clients based WiFi network.

In the fixed WiFi network, ONOE showed a relatively good performance result, so the long term statistics based bit-rate selection would perform well in this environment. It had the performance difference with a factor of 0.995 and 0.995 from AMRR and 54 Mbps, respectively.

It also performed relatively well in the single-vehicular WiFi network. It showed the performance difference with a factor of 0.978 and 0.994 from RRAA and 36 Mbps. Moreover, it has almost a 0% error rate.

However, it does not quickly respond to the rapid channel condition change in the multiple clients based vehicular WiFi network (e.g., fixed-mobile WiFi network, multi-vehicular WiFi network). In the fixed-mobile WiFi network, it had the performance difference with a factor of 0.717, 0.867, 0.880 and 0.885 from OHBR, RRAA, 48 Mbps and MDRS, respectively. In the multi-vehicular WiFi network, it shows the worst performance with a factor of 0.585, 0.677, 0.714 and 0.734 from OHBR, MDRS, 48 Mbps fixed bit-rate and 54 Mbps fixed bit-rate, respectively. Therefore, ONOE was not consistent across the various scenarios in terms of throughput.

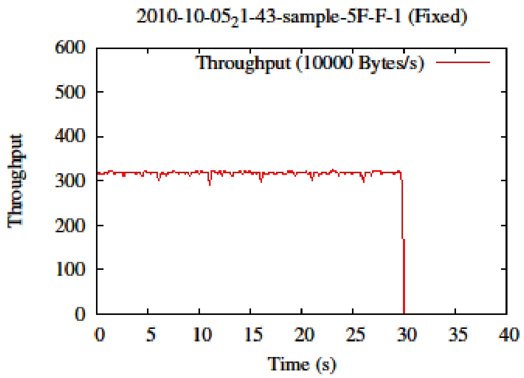
Relatively, ONOE does not show a good fairness result. Especially, in the multi-vehicular network, it had the worst result (a factor of 0.51 between 1st WiFi client and 2nd WiFi client) among all evaluated bit-rate selection algorithms. According to the diagrams in Section 0 and 0, it is very clear that the 2nd vehicular WiFi client had a poor performance result as compared to the 1st vehicular WiFi client. This fact seems to be a clear indication that either the long-term statistics based approach or the implementation of ONOE significantly affects the fairness in multi-vehicular WiFi networks.

From the above result, we may intuitively think the long-term statistics based bit-rate selection algorithm may not perform well in vehicular WiFi networks. Relatively, the short-term variations based bit-rate selection algorithm such as AMRR and RRAA would be more effective than the long-term variations based bit-rate selection algorithms in vehicular WiFi networks.

5.2.4 SAMPLE

SAMPLE is a probing-based adaptive bit-rate selection algorithm.

In the single fixed WiFi network, it did not perform well as compared to the other adaptive bit-rate selection algorithms. From our experiment, the WiFi client is placed in the highest bit-rate coverage area and other adaptive bit-rate selection algorithms approached to the best bit-rate (54 Mbps), so they seem to obtain good performance results. However, SAMPLE seems to estimate the bit-rate close to 36 Mbps fixed bit-rate. Compared to other adaptive bit-rate selection algorithms, SAMPLE seems to be conservative with the fixed WiFi client. Figure 14 shows the performance comparison of SAMPLE with other bit-rate selection algorithms in the single fixed WiFi network. SAMPLE and 36 Mbps fixed bit-rate were almost identical.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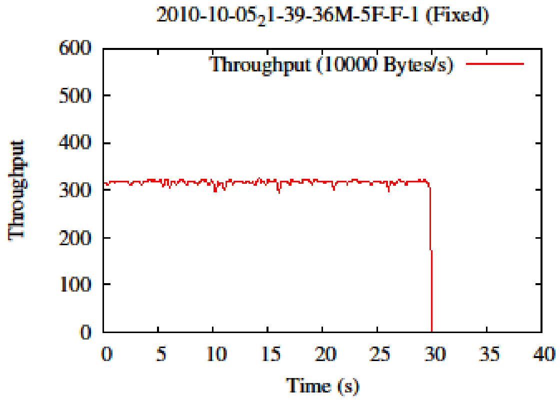
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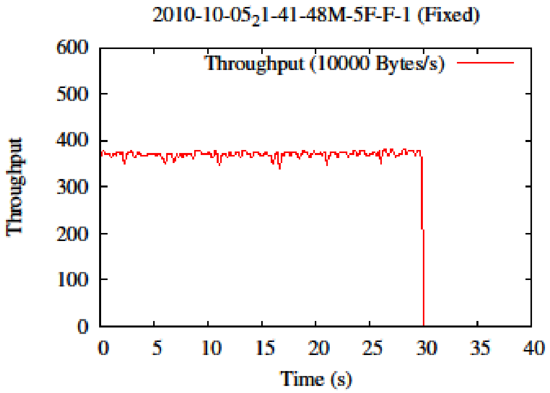
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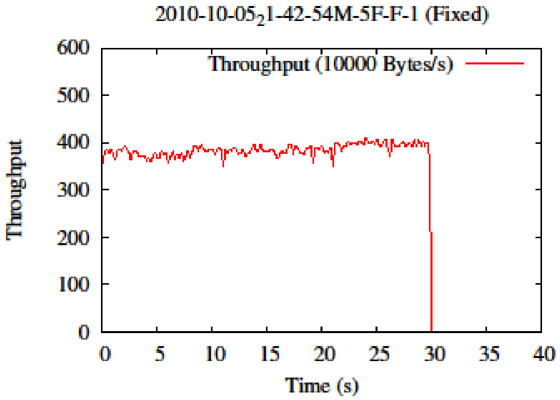
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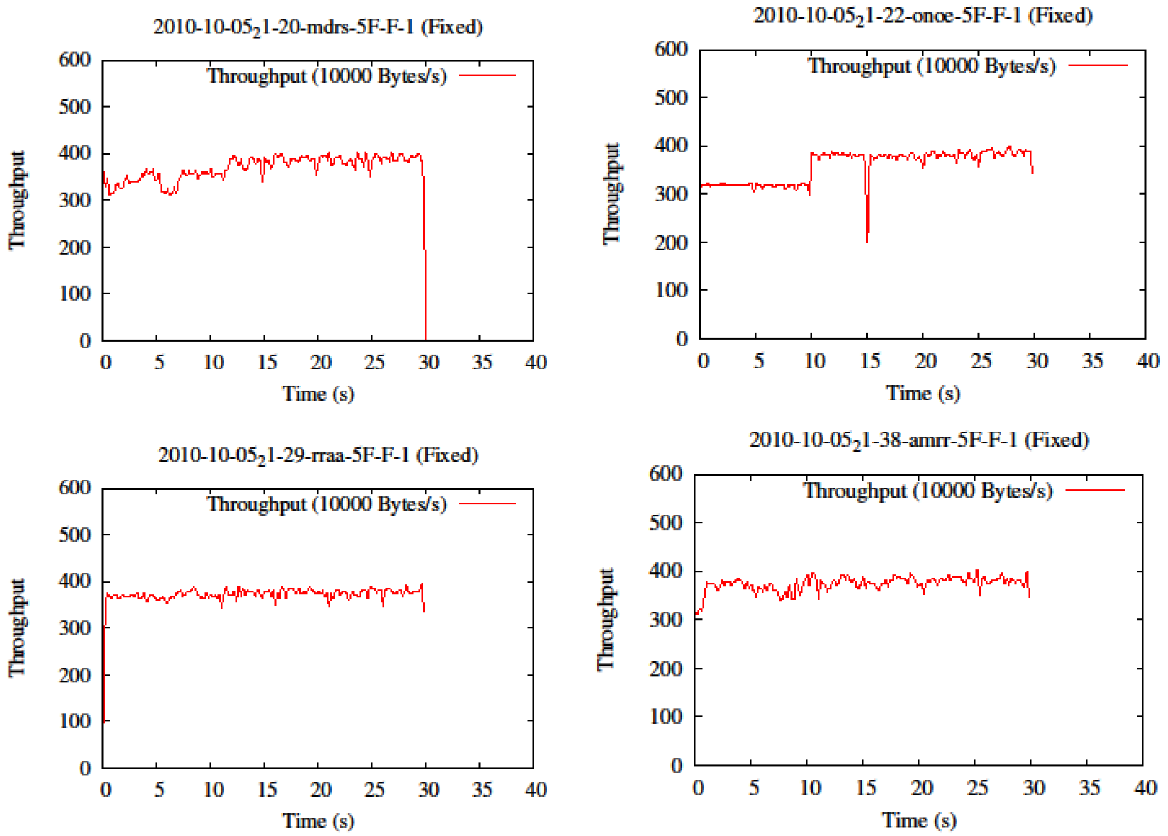

Figure 14: Performance comparison for SAMPLE in single fixed WiFi network

Unlike the case in the single fixed WiFi network, SAMPLE had a relatively good performance result in the vehicular WiFi network. It is also consistent across the various scenarios (e.g., the single-vehicular WiFi network, the fixed-mobile WiFi network and the multi-vehicular WiFi network).

In the single-vehicular WiFi network, SAMPLE performed with a factor of 0.96 lower than RRAA which had the best performance. In the fixed-mobile WiFi network, SAMPLE differs the performance with a factor of 0.79, 0.956, 0.976, and 1.005 from OHBR, RRAA, MDRS and AMRR, respectively. In the multi-vehicular WiFi network, the performance of SAMPLE differs with a factor of 0.717, 0.831 and 1.006 from OHBR, MDRS and RRAA, respectively.

Relatively, SAMPLE does not show a good fairness result (0.22 in the fixed-mobile WiFi network, 0.25 in the multi-vehicular WiFi network).

Therefore, it is hard to insist that SAMPLE is an effective bit-rate selection algorithm in multiple clients based vehicular WiFi networks.

5.2.5 RRAA

RRAA is the short-term loss rate statistics based approach. Like AMRR, it seems to quickly adapt to the channel condition change. The algorithm shows relatively good performance in the vehicular WiFi network. In our experiments, the performance result is relatively consistent and good across the available scenarios (e.g., single-fixed, single-vehicular, fixed-mobile and multi-vehicular WiFi networks).

In the single fixed WiFi network, RRAA shows relatively good performance compared to other bit-rate selection algorithms. It shows the performance difference with a factor of 0.993, 0.993, 0.996 and 1.018 from AMRR, 54 Mbps, 48 Mbps and MDRS, respectively.

In the single-vehicular WiFi network, it shows the best performance among all the bit-rate selection algorithms. It performed with a factor of 1.016, 1.022 and 1.03 higher than 36 Mbps, ONOE and AMRR. It also shows the best performance in the fixed-mobile WiFi network, among the adaptive bit-rate selection algorithms. It shows the performance difference with a factor of 0.827, 1.016, and 1.021 from OHBR, 48 Mbps and MDRS, respectively. In the multi-vehicular WiFi network, it performed with a factor of 0.713, 0.826, 0.876, 0.895, 0.994 and 0.996 lower than OHBR, MDRS, 48 Mbps, 54 Mbps, SAMPLE and 36 Mbps, respectively.

As RRAA is the loss rate based algorithm, it has certain data losses (9.32% in the single-fixed WiFi network, 20.2% in the single-vehicular WiFi network, 13.3% in the fixed-mobile WiFi network and 20.01 in the multi-vehicular WiFi network). Relatively, it has more data losses in vehicular WiFi clients than fixed WiFi clients. According to the relevant diagrams in Appendix, it is clear that RRAA over-estimates the transmission rate, so it has significant data losses during data transmission.

RRAA shows relatively good fairness compared to other bit-rate selection algorithms.

Given the performance result of throughput and fairness, RRAA seems to be an effective bit-rate selection algorithm in the various WiFi networks.

5.2.6 MDRS

MDRS is a vehicular WiFi network-focused adaptive bit-rate selection algorithm. It is based on the loss-rate versus RSSI according to the fact that in a mobile network error rate versus RSSI plots are consistent for each link rate across different scenarios. It can also adjust the degree of asymmetry between a sender and a receiver [3].

According to the diagrams in Appendix, MDRS seems to be similar with RRAA and AMRR in terms of the shape of adaptation to the network condition changes. So, MDRS responds to the channel condition change quickly. However, it seems to be more aggressive than RRAA and AMRR and it shows that the performance result is inconsistent across the scenarios, especially in the single-vehicular WiFi network. It performed well in the multiple clients based vehicular WiFi network, especially in the multi-vehicular WiFi network.

In general, MDRS shows a good performance result as compared to other bit-rate selection algorithms although it shows a bad performance result (the single-vehicular WiFi network) in some scenarios due to the high error (50%).

In the single fixed WiFi network, MDRS shows the performance difference with a factor of 0.976, 0.975, 0.982 and 1.022 from 54 Mbps, AMRR, RRAA and ONOE, respectively. In the single-vehicular WiFi network, MDRS shows a bad performance result due to the high error rate (50%). It performed with a factor of 0.695, 0.710, 0.717 and 0.725 lower than RRAA, ONOE, AMRR and SAMPLE, respectively.

In the fixed-mobile WiFi network, it shows the performance difference with a factor of 0.809, 0.979, and 1.025 from OHBR, RRAA and SAMPLE, respectively. In the multi-vehicular WiFi network, it shows the performance difference with a factor of 0.863 and 1.204 from OHBR and SAMPLE, respectively.

According to Figure 13, MDRS shows a relatively good fairness result in the multi-vehicular WiFi network.

MDRS seems to be one of the most effective bit-rate selection algorithms among the bit-rate selection algorithms. It was the second best bit-rate selection algorithm following OHBR.

5.2.7 OHBR

OHBR is an opportunistic highest fixed bit-rate-based method focusing on specifically roadside vehicular WiFi networks. It sends data only to the vehicles which are within the highest bit-rate coverage area.

We tested OHBR with only the multiple WiFi clients based scenarios, such as the fixed-mobile WiFi network and the multi-vehicular WiFi network. The reason being that the algorithm is based on an assumption that in practice of the vehicular WiFi network, at least one vehicle exists in the highest bit-rate coverage algorithm. Therefore, the single-vehicular WiFi network, which could have chance with no vehicle in the highest bit-rate coverage area in a certain time, is not considered.

According to our test results, OHBR shows a significant performance difference from other bit-rate selection algorithms. In the fixed-mobile WiFi network, it performed a factor of 1.2096 and 1.228, significantly better than RRAA and 48 Mbps, respectively. In the multi-mobile WiFi network, it also performed a factor of 1.158 and 1.229, significantly better than MDRS and 48 Mbps, respectively. Therefore, OHBR shows significant performance improvement in roadside multi-vehicular WiFi networks.

From Figure 11 and Figure 13, we found two attributes that may affect fairness, degree of mobility for the WiFi clients in the network and an effective fairness mechanism for the fixed WiFi client. The degree of mobility (in other words, degree of similarity for the pattern of staying in a roadside multi-vehicular WiFi network for all the WiFi clients) seems to be a critical attribute that affects the fairness. For example, like the scenario in the multi-vehicular WiFi network, if all the WiFi clients move on the road, the fairness would be very high (0.05). However, if there are fixed WiFi clients that stay within the highest bit-rate coverage area, fairness would be very poor (0.7). Or, the time for data transmission for the fixed WiFi client would be similar to the time of data transmission for the vehicular WiFi client, in which the fairness would be high. This means that an effective method to control the time spending on data transmission for the fixed WiFi client may help improve fairness. The time-based fairness can be considered to be used for controlling the duration of data transmission for the fixed WiFi clients in the highest bit-rate coverage area.

Chapter 6

Conclusions and Future Works

6.1 Conclusions

Bit-rate selection algorithm is one of the crucial components in 802.11 in terms of throughput. For the last decades many research have been done to improve the performance and the functionality of bit-rate selection. As a result, many effective adaptive bit-rate selection algorithms have been proposed and significantly improved the performance of throughput. However, due to the limited selected network circumstances and scenarios for evaluating the algorithms, it is hard to firmly agree that the adaptive bit-rate selection algorithms are really performed well regardless of any circumstances.

Many experimental analysis based research have performed on the adaptive bit-rate selection algorithms. Most of them have been done in fixed WiFi networks and produced remarkable results. Much research has been done in vehicular WiFi networks as well. However, their focuses were not specific towards the bit-rate selection algorithms.

Some research focused on the bit-rate selection algorithms in vehicular WiFi networks, but was mostly based on the single WiFi client. Little research was performed in multi-vehicular WiFi networks, but was based on simulation. As a result, it is hard to agree that the adaptive bit-rate selection algorithms are effective for the multi-vehicular WiFi network in terms of the performance of throughput for the entire network and the individual WiFi client, especially in roadside multi-vehicular WiFi network. In addition, another concern in the adaptive bit-rate selection algorithms is complexity. Obviously any adaptive bit-rate selection algorithm is more complicated than the fixed bit-rate-based method. Therefore, it is questioned if adaptive bit-rate selection algorithms are always appropriate in any WiFi network circumstances. For this question, we conducted extensive experiments in the several vehicular WiFi network scenarios with various bit-rate selection algorithms to figure out the following:

1. Performance of adaptive bit-rate selection algorithms and the fixed bit-rate in roadside multi-vehicular WiFi networks.
2. If the adaptive bit-rate selection algorithm works well in roadside multi-vehicular WiFi networks compared to the fixed bit-rates.

3. The way to improve performance and functionality of the bit-rate selection algorithms in roadside multi-vehicular WiFi networks in terms of throughput of the entire network and fairness of individual throughput for each WiFi client.

Along with the conducted experimental analysis, we researched for a simple and better performed transmission-rate decision algorithm in roadside multi-vehicular WiFi networks based on some intuitive thoughts. In a recent research [1], the exploit of network environment knowledge is recommended to improve the WiFi network performance. The research indicates that the performance of opportunistic vehicular data transfer is significantly improved by using such environment information. In a roadside vehicular WiFi network, there are several obvious valuable facts. First, each vehicular WiFi client enters and stays in the highest bit-rate coverage area for a certain period. Second, if the residence time in the highest bit-rate coverage area is long enough, the throughput in that coverage area is getting closer to the entire throughput of the vehicle in the WiFi coverage area [2]. Based on the above facts, the network may use only the highest bit-rate for all the vehicular WiFi clients when they enter the highest bit rate coverage area and maximize the entire network throughput.

Therefore, in a roadside vehicular WiFi network, the highest fixed bit-rate may perform better than any adaptive bit-rate selection algorithms in terms of the entire network throughput performance. In addition to the performance, the implementation and the operation of the fixed highest bit-rate is much simpler than that of any adaptive bit-rate selection algorithms.

During the experiments, we observed the followings:

1. Overall, the adaptive bit-rate selection algorithms performed well in roadside multi-vehicular WiFi networks in terms of the entire network and fairness of individual throughput across the WiFi clients.
2. However, some fixed bit-rates, such as 48 Mbps and 54 Mbps, also performed well, and even performed better than some of the adaptive bit-rate selection algorithms. This result indicates that the higher fixed bit-rates may be more effective than the adaptive bit-rate selection algorithms in roadside multi-vehicular WiFi networks because of the similar or better performance and fairness and the simplicity of the algorithm.
3. Furthermore, we found that OHBR, which is an opportunistic highest bit-rate selection algorithm, performed significantly better than any other algorithms in terms of not only

throughput but also fairness. Therefore, we believe that OHBR is the most effective bit-rate selection algorithm in roadside multi-vehicular WiFi networks than any other bit-rate selection algorithms.

6.2 Limitations and Future Works

The biggest limitation of our research is the experimental analysis in a lab environment. We admit that there would be some environmental differences from which could cause different performance results. Therefore, our experimental results must be confirmed with another experiment from a real roadside multi-vehicular WiFi network in various scenarios in the future.

In our experimental analysis, we demonstrated that OHBR outperformed, as compared to the other bit-rate selection algorithms. However, there were some assumptions and limitations that must be addressed in the future:

1. OHBR was proposed and evaluated based on some assumptions. First, as the algorithm focuses on multi-vehicular WiFi networks, single vehicular WiFi networks were not taken into consideration. However, in order to make OHBR become a more practical and useful algorithm, single vehicular WiFi networks should also be addressed in the future. Second, we assumed that at least one vehicular WiFi client always exists in the highest bit-rate coverage area. The assumption was made according to the following reasons:

    - In a real multi-vehicular WiFi network, many vehicles would be placed in the network for the given time.
    - Each vehicle always enters and stays in the highest bit-rate coverage area in a certain time period.

    According to the above reasons, we believed that at least one vehicular WiFi client would always exist in the highest bit-rate coverage area. However, OHBR must also be applied to the circumstance of no highest bit-rate vehicular WiFi client available for the given time. Therefore, the circumstance of no highest bit-rate vehicular WiFi client available for a moment must be addressed in the future.

2. As our research was based on experimental analysis, no mathematical model for OHBR has been made yet. Therefore, in order to make OHBR become a proven effective algorithm, a mathematical model must be provided and followed by the simulation based analysis.
3. According to our test result, OHBR shows the worst fairness in the fixed-mobile WiFi network, among all the bit-rate selection algorithms. The main reason was that if a fixed WiFi client resides in the highest bit-rate coverage area, it would continually receive data from the AP and would be the best performing WiFi client in the network. And, if a fixed WiFi client resides outside of the highest bit-rate coverage area, it will not receive any data from the AP. Therefore, there will be a fairness problem in fixed-mobile WiFi networks. OHBR needs to resolve the fairness problem in fixed-mobile WiFi networks.

We observed that MDRS was the best algorithm with the highest data-transmission rate at the sender. However, it sometimes didn't perform well, especially in the single-vehicular WiFi network due to the big error rate occurred by over-estimation of transmission rate. In order to improve the performance of MDRS, the significant error rate must be reduced. Therefore, this problem should be addressed in the future.

In multi-client-based WiFi networks, we found that the fixed bit-rates for 802.11b performed extremely well in terms of fairness, as compared to any other bit-rate selection algorithms including the fixed bit-rates for 802.11g. It would be worthy to figure out the followings:

1. Why 802.11b and 802.11g show different fairness result?
2. Why 802.11b has very good fairness?
3. Why the fairness result of 802.11g was not as good as that of 802.11b? The fairness result of 802.11g seems to be affected by the network channel conditions of the WiFi clients.

We also found that ONOE had the worst fairness in multi-vehicular WiFi networks. It is clear that either the long-term statistics based approach or the implementation of ONOE affects the fairness. Therefore, it is worthy to investigate on the reason for the future.

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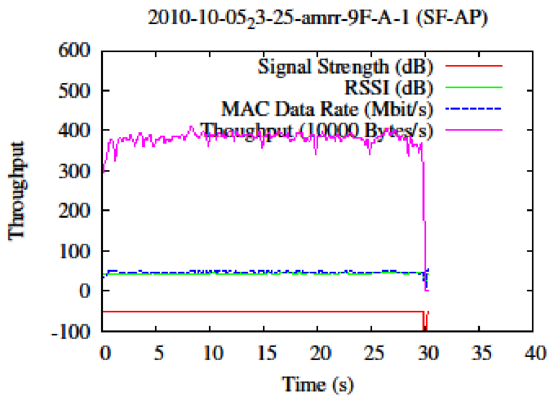
Appendix A: Detailed Results

A.1 Single Fixed WiFi Network

The following diagrams depict the data transfer progress for each individual bit-rate selection algorithm in the single fixed WiFi network.

A.1.1 AP



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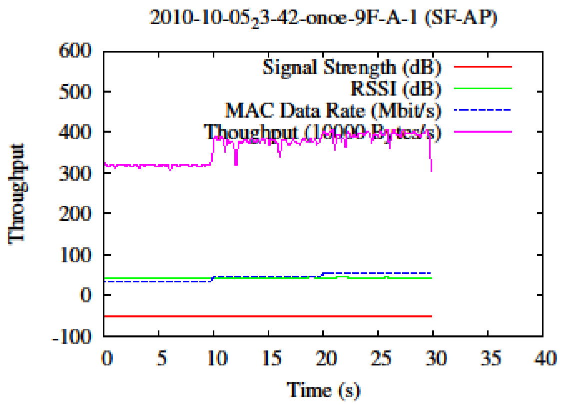

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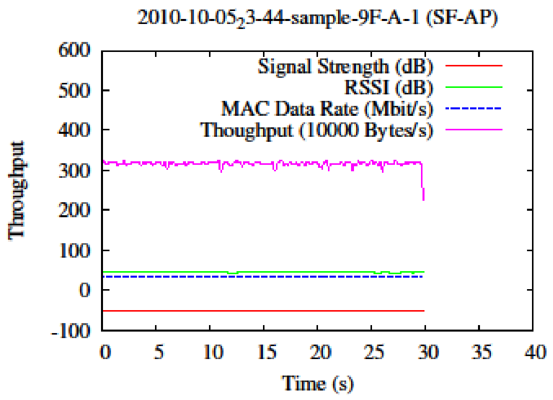

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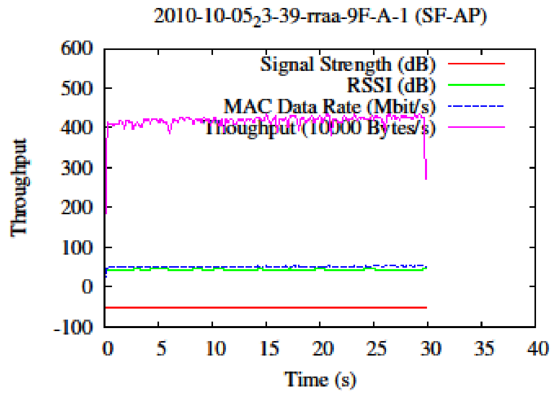

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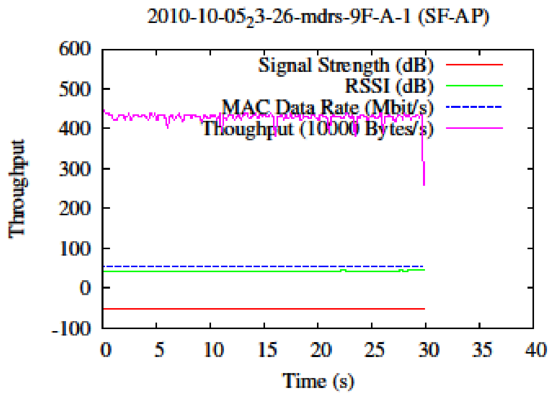
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RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
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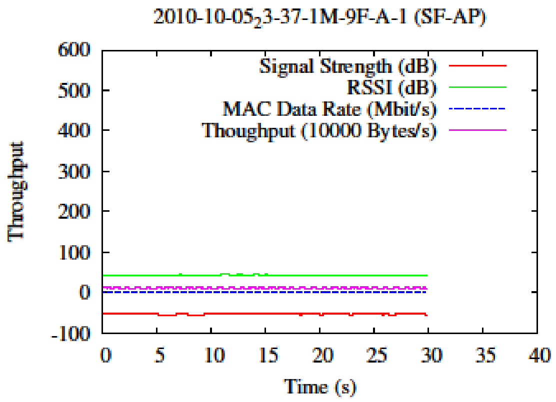
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MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
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Time (s)
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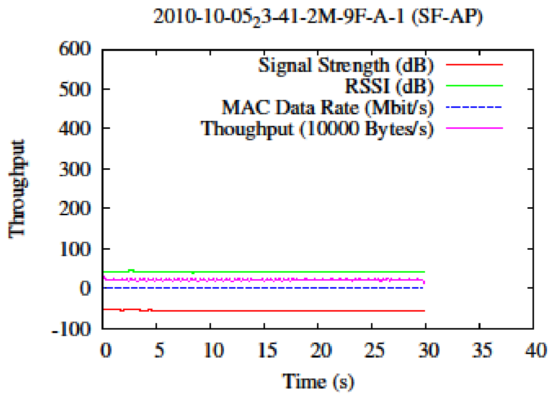
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MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
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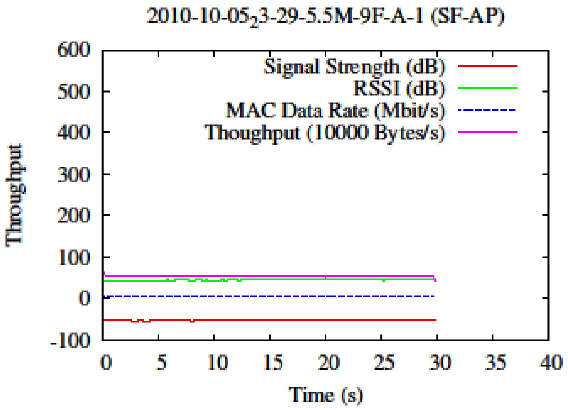
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RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
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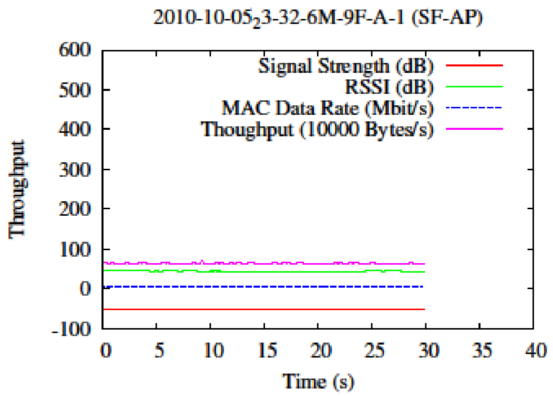
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RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
Time (s)
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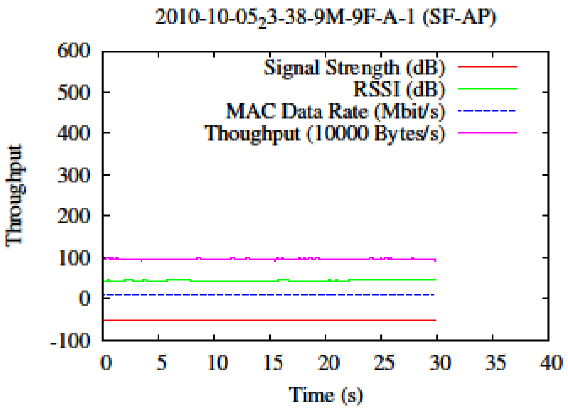
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MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
Time (s)
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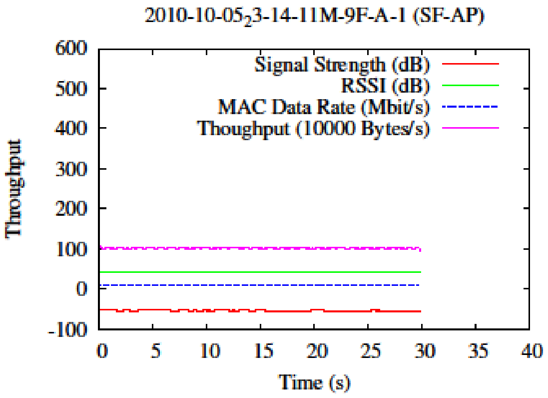
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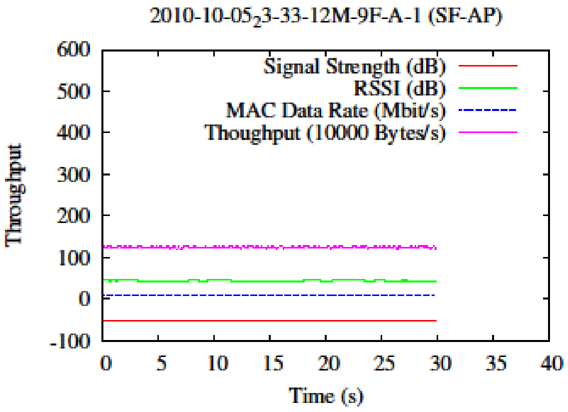
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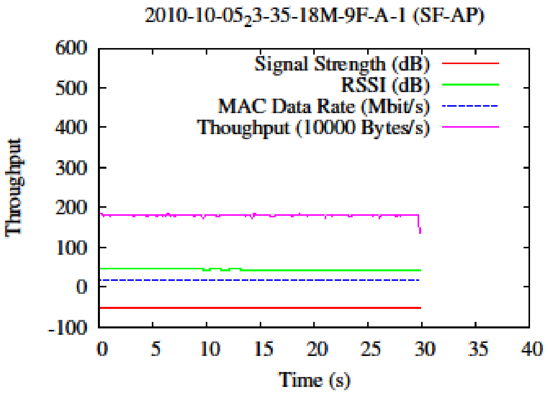
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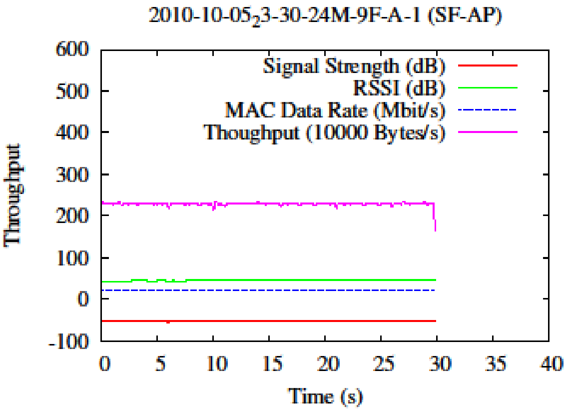
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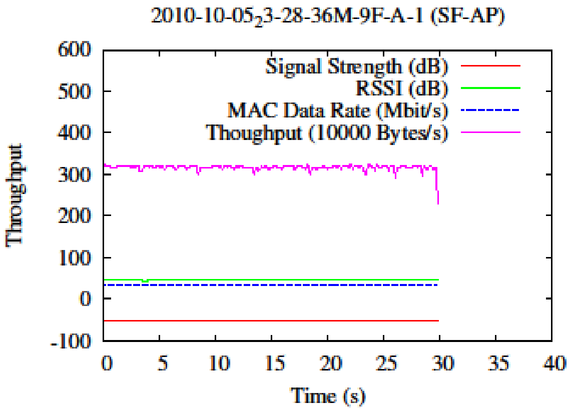
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RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
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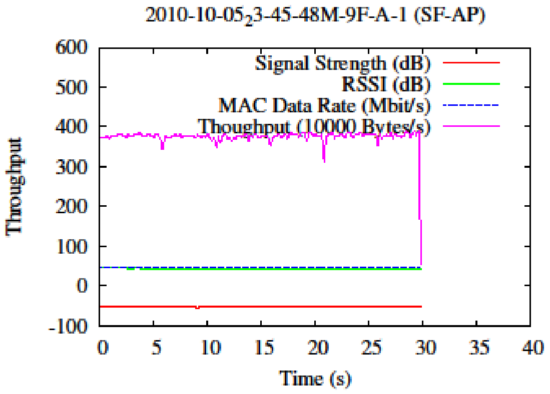
Time (s)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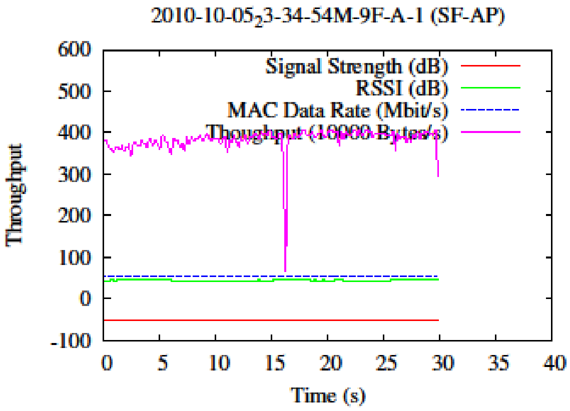
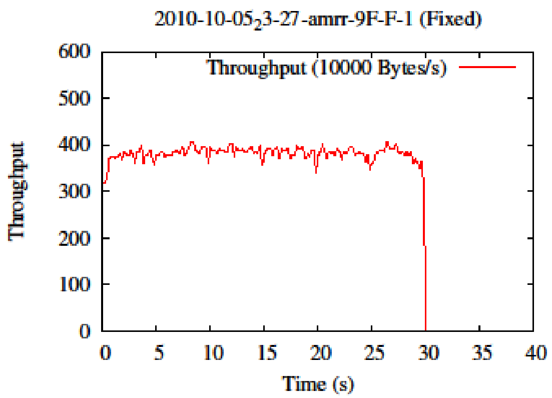
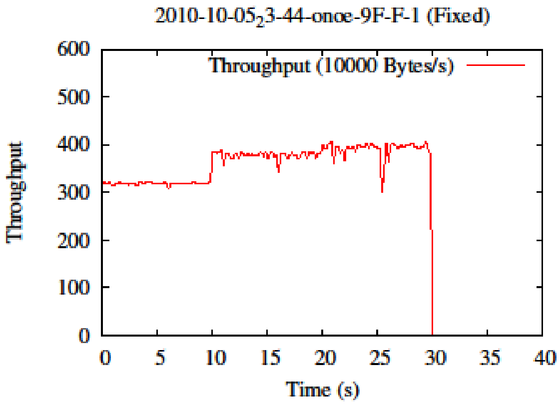
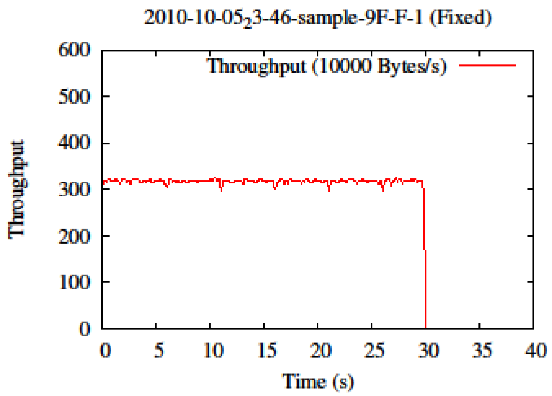
Time (s)

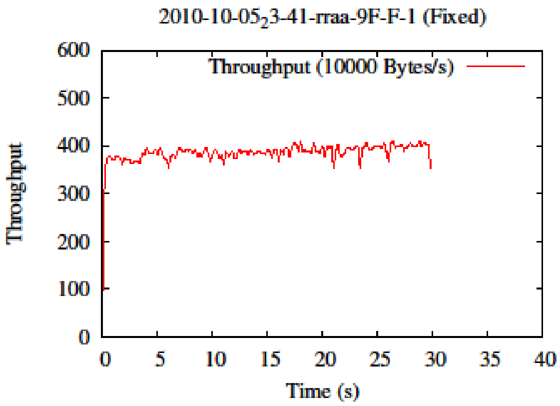

2010-10-05$_2$3-34-54M-9F-A-1 (SF-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

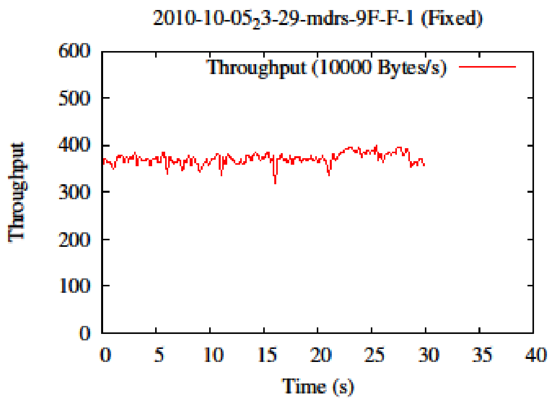
A.1.2 Fixed WiFi Client

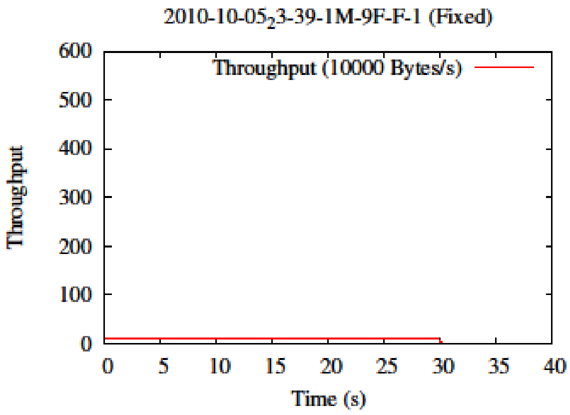


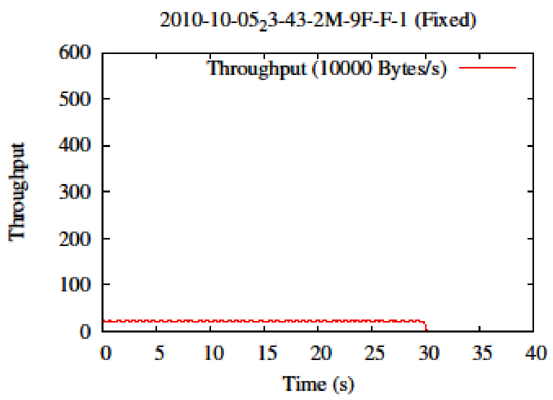


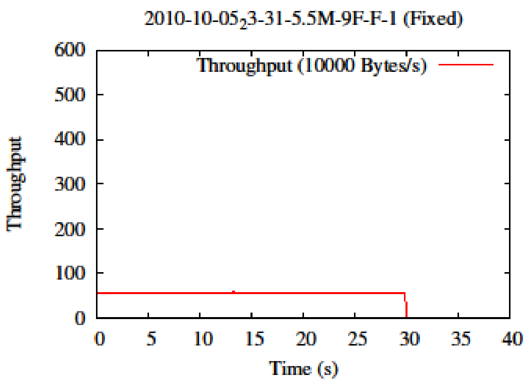


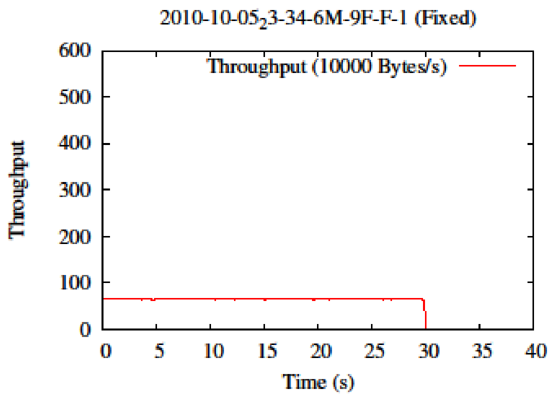


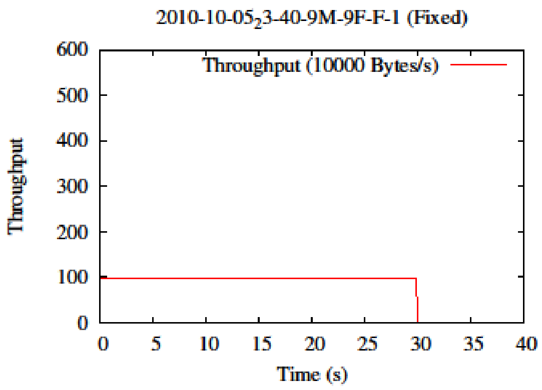


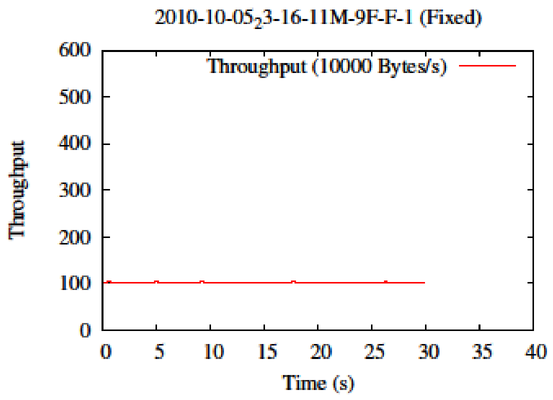


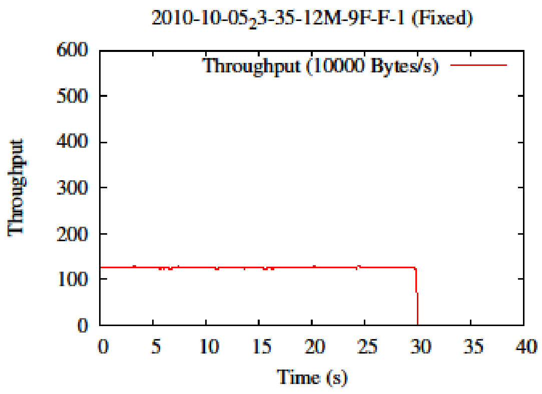

2010-10-05$_2$3-43-2M-9F-F-1 (Fixed)

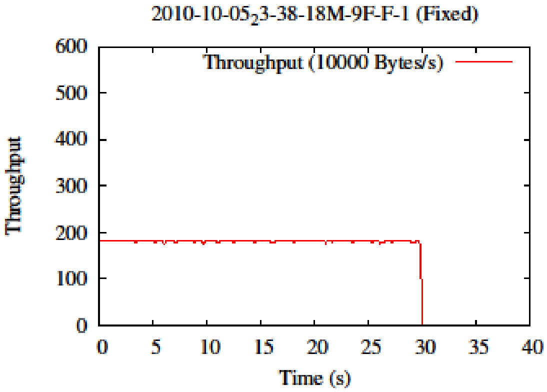

2010-10-05$_2$3-31-5.5M-9F-F-1 (Fixed)

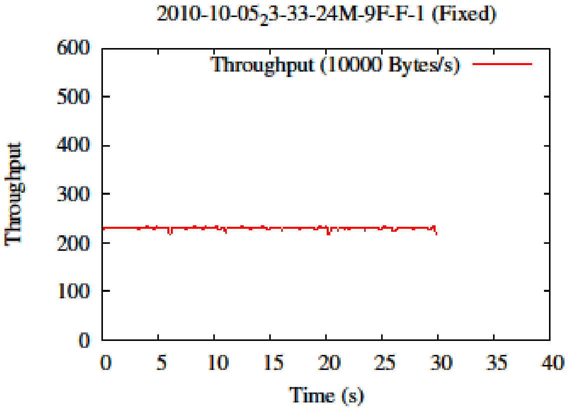

2010-10-05$_2$3-34-6M-9F-F-1 (Fixed)

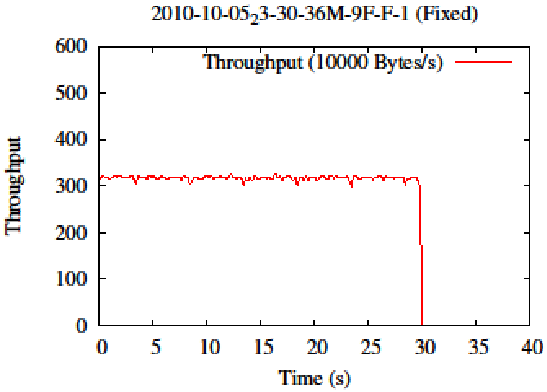

2010-10-05$_2$3-40-9M-9F-F-1 (Fixed)

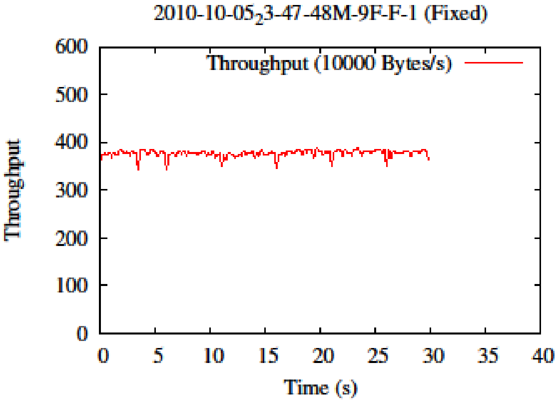

2010-10-05$_2$3-16-11M-9F-F-1 (Fixed)

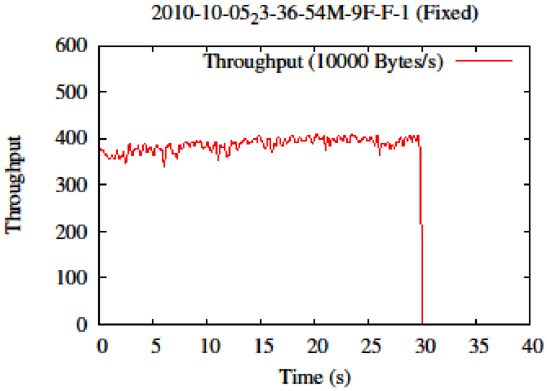

2010-10-05$_2$3-35-12M-9F-F-1 (Fixed)


2010-10-05$_2$3-38-18M-9F-F-1 (Fixed)


2010-10-05$_2$3-33-24M-9F-F-1 (Fixed)


2010-10-05$_2$3-30-36M-9F-F-1 (Fixed)


2010-10-05$_2$3-47-48M-9F-F-1 (Fixed)

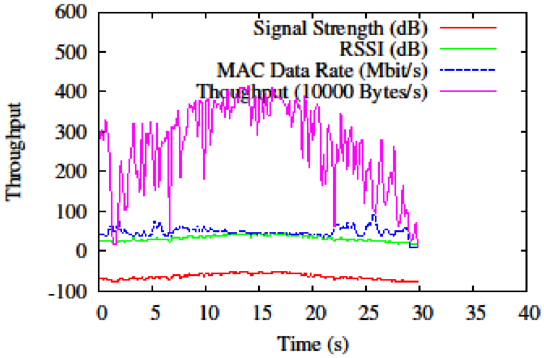

2010-10-05$_2$3-36-54M-9F-F-1 (Fixed)

A.2 Single-Vehicular WiFi Network

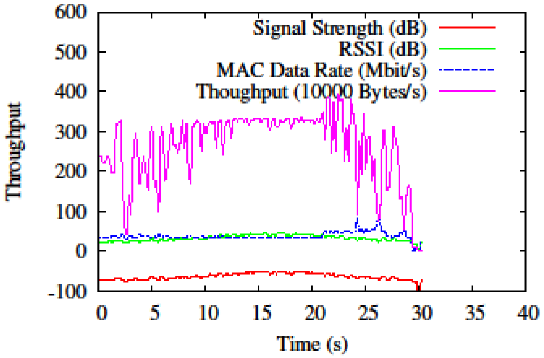
The following diagrams depict the data transfer progress for each individual bit-rate selection algorithm in the single-vehicular WiFi network.

A.2.1 AP

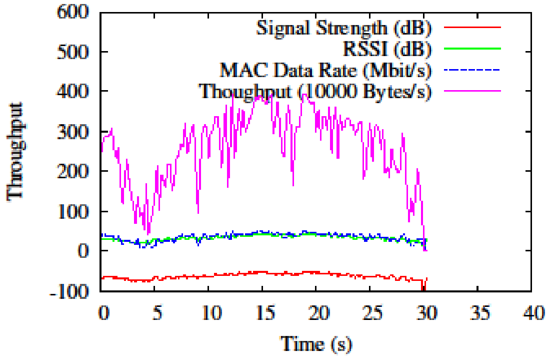
2010-10-09$_1$0-06-amrr-1M-A-1 (SM-AP), Mar 16



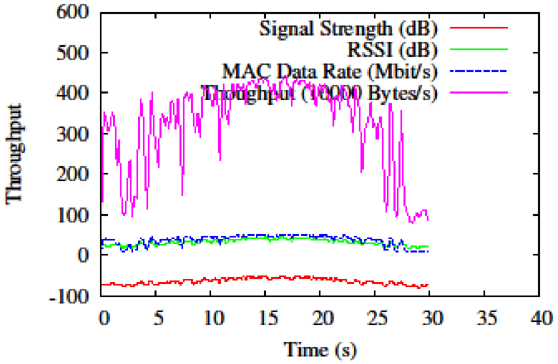
2010-10-09$_1$0-12-onoe-1M-A-1 (SM-AP), Mar 16



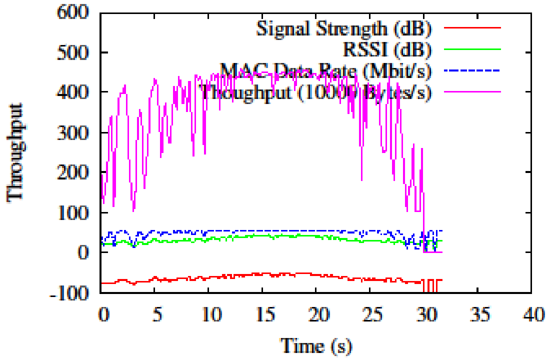
2010-10-10$_1$3-15-sample-1M-A-1 (SM-AP), Mar 16



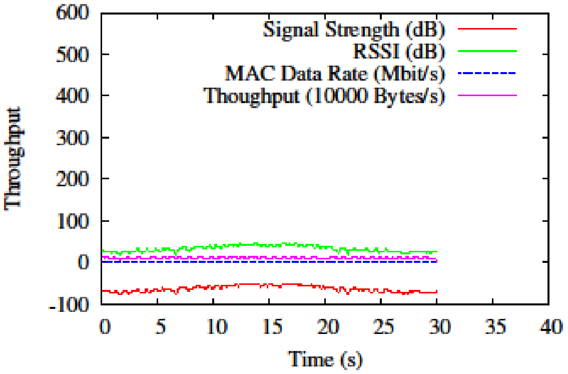
2010-10-09$_0$9-47-rraa-1M-A-1 (SM-AP), Mar 16

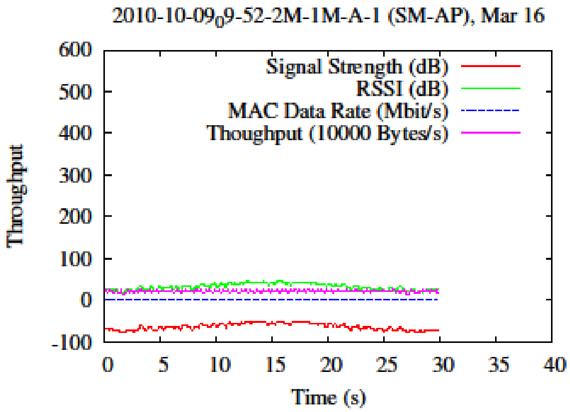


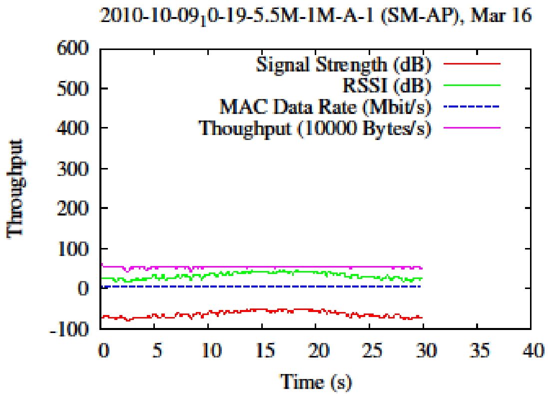
2010-10-09$_1$0-17-mdrs-1M-A-1 (SM-AP), Mar 16

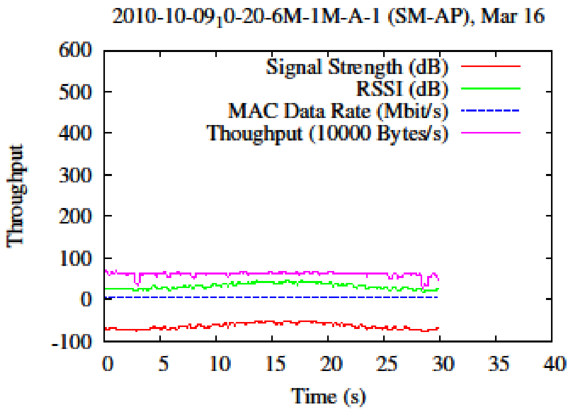


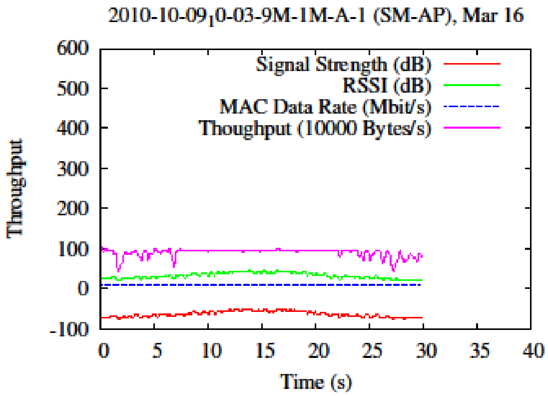
2010-10-09$_1$0-00-1M-1M-A-1 (SM-AP), Mar 16

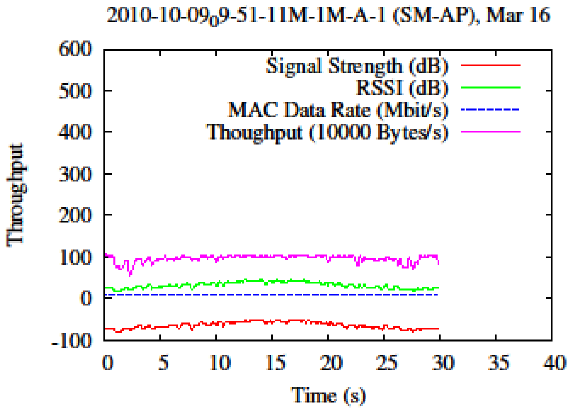


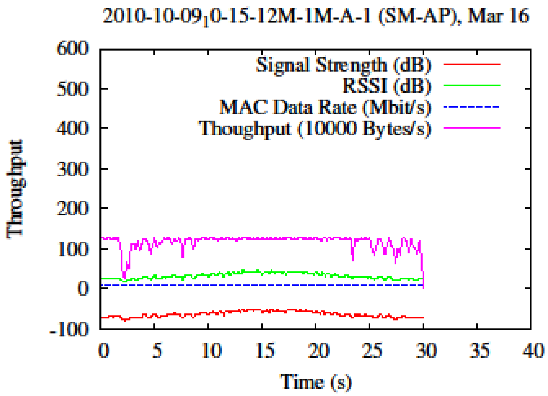

2010-10-09$_0$9-52-2M-1M-A-1 (SM-AP), Mar 16


2010-10-09$_1$0-19-5.5M-1M-A-1 (SM-AP), Mar 16

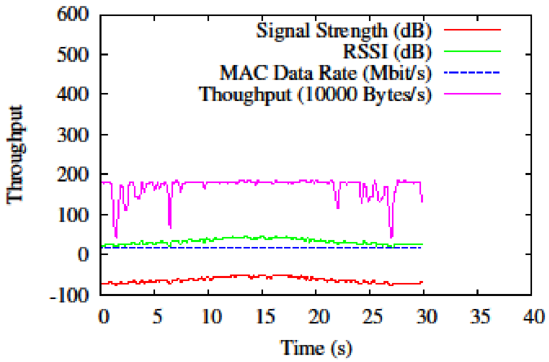

2010-10-09$_1$0-20-6M-1M-A-1 (SM-AP), Mar 16


2010-10-09$_1$0-03-9M-1M-A-1 (SM-AP), Mar 16

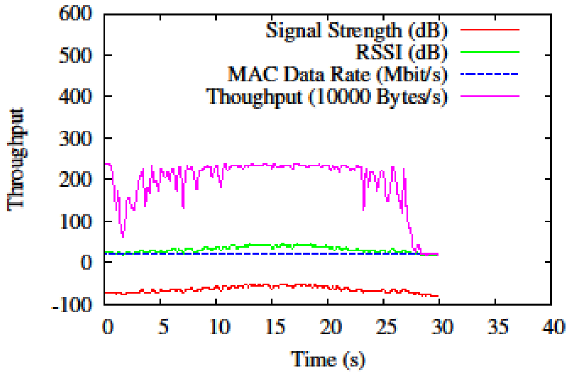

2010-10-09$_0$9-51-11M-1M-A-1 (SM-AP), Mar 16


2010-10-09$_1$0-15-12M-1M-A-1 (SM-AP), Mar 16

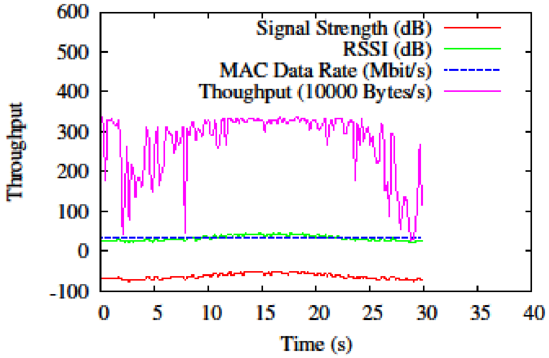
2010-10-09$_0$9-59-18M-1M-A-1 (SM-AP), Mar 16



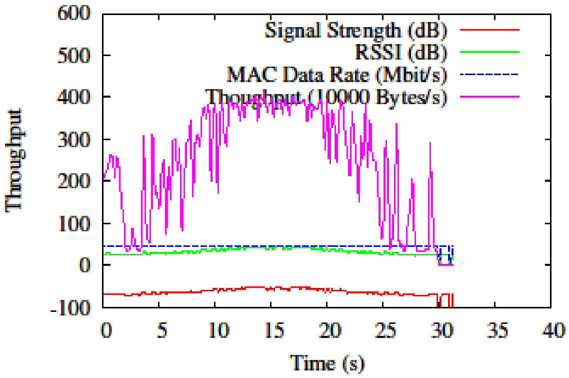
2010-10-09$_0$9-49-24M-1M-A-1 (SM-AP), Mar 16



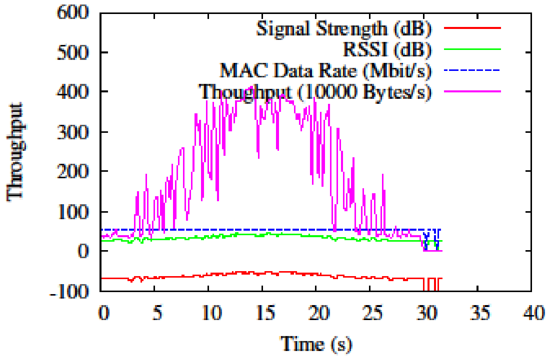
2010-10-09$_1$0-14-36M-1M-A-1 (SM-AP), Mar 16



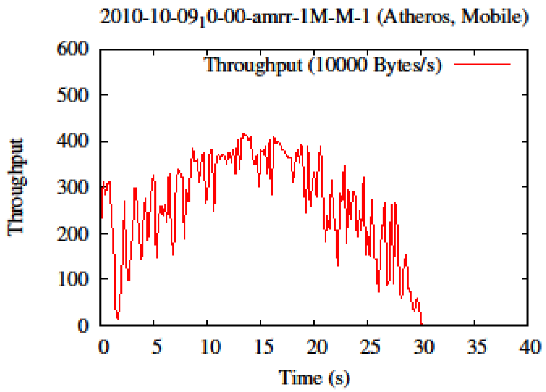
2010-10-09$_1$0-09-48M-1M-A-1 (SM-AP), Mar 16

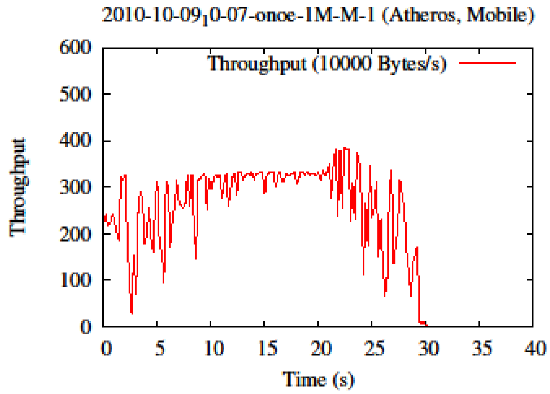


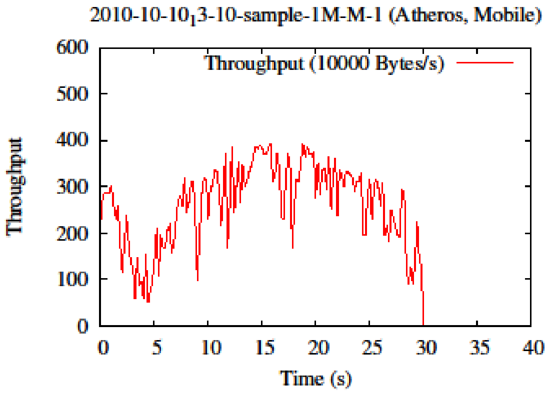
2010-10-09$_0$9-56-54M-1M-A-1 (SM-AP), Mar 16

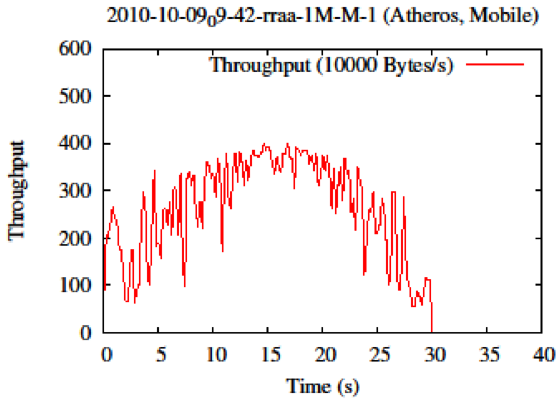


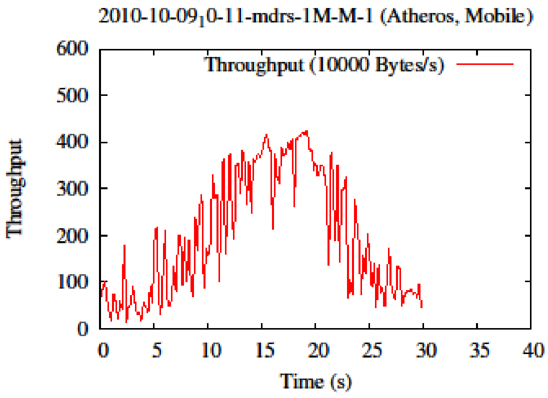
A.2.2 Vehicular WiFi Client

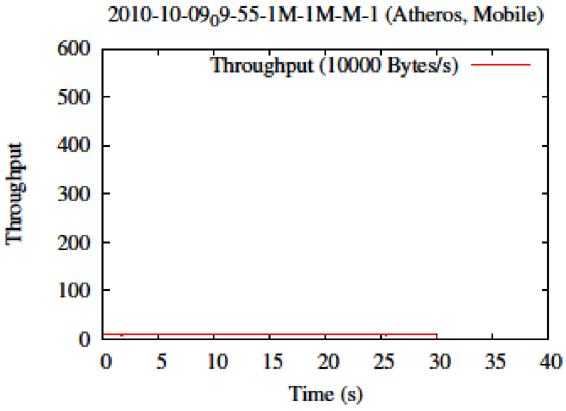




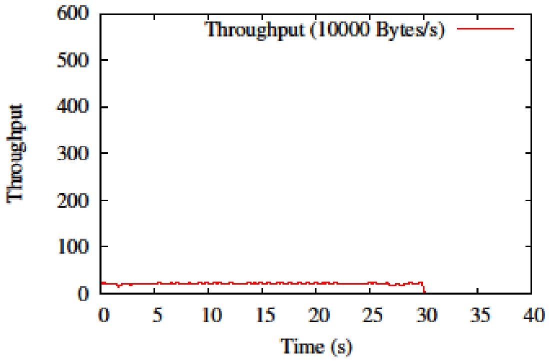




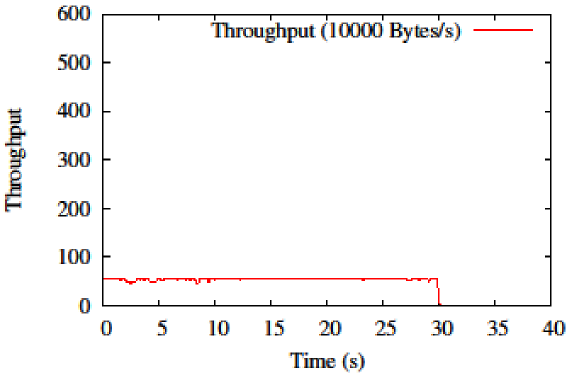




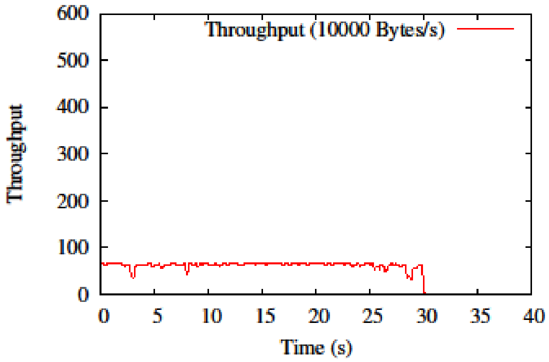
2010-10-09$_0$9-47-2M-1M-M-1 (Atheros, Mobile)



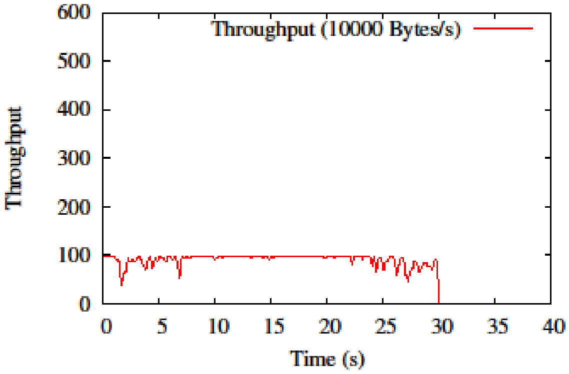
2010-10-09$_1$0-13-5.5M-1M-M-1 (Atheros, Mobile)



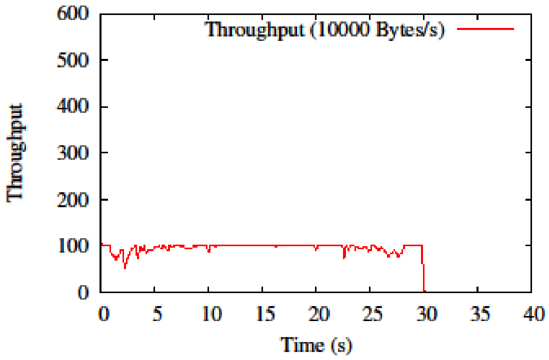
2010-10-09$_1$0-15-6M-1M-M-1 (Atheros, Mobile)



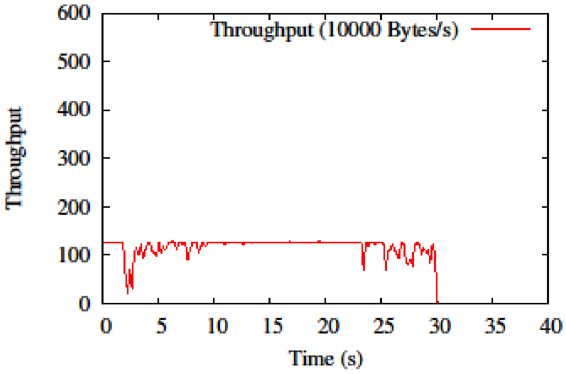
2010-10-09$_0$9-58-9M-1M-M-1 (Atheros, Mobile)

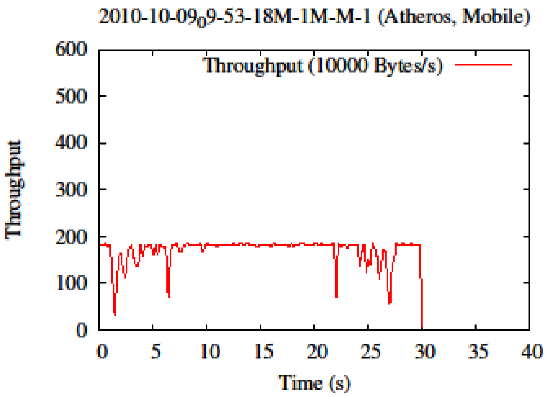


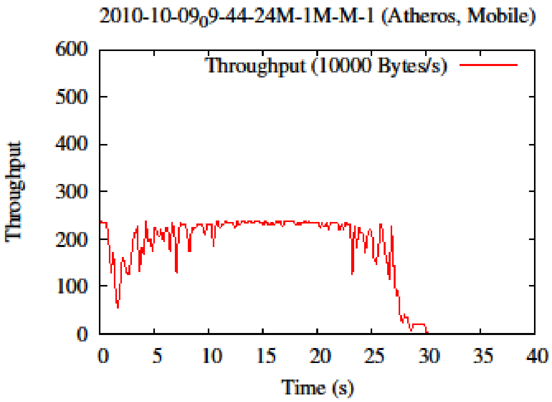
2010-10-09$_0$9-45-11-1M-M-1 (Atheros, Mobile)

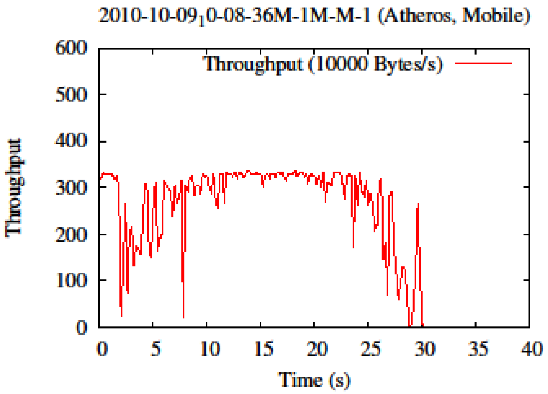


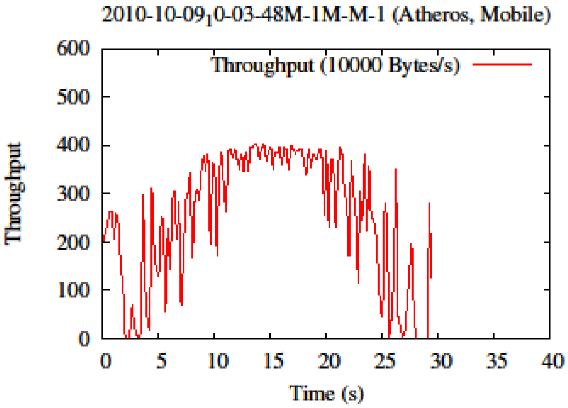
2010-10-09$_1$0-10-12M-1M-M-1 (Atheros, Mobile)

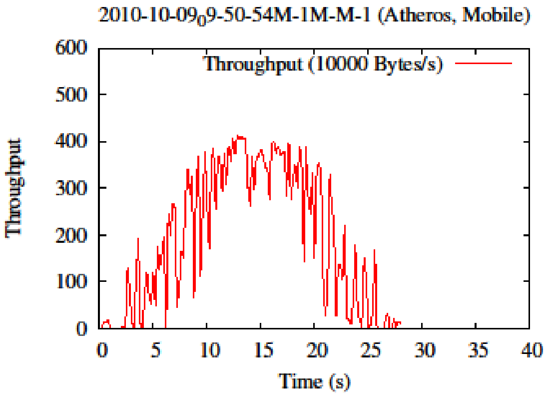



2010-10-09$_0$9-53-18M-1M-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
Time (s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40


2010-10-09$_0$9-44-24M-1M-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
Time (s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40


2010-10-09$_1$0-08-36M-1M-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
Time (s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40

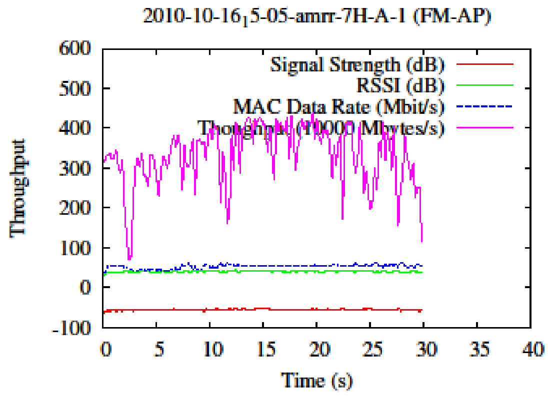

2010-10-09$_1$0-03-48M-1M-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
Time (s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40

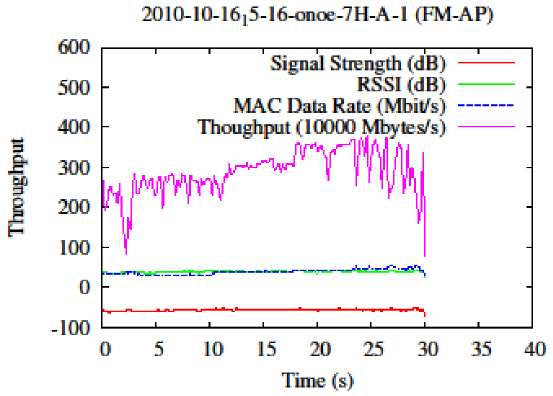

2010-10-09$_0$9-50-54M-1M-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
Time (s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40

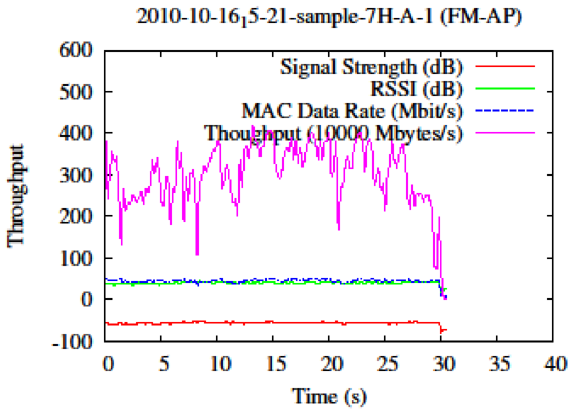
A.3 Mobile-Fixed WiFi Network

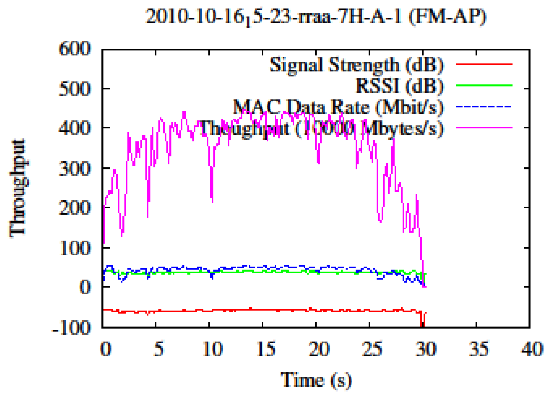
The diagrams in the following sections depict the data transfer progress for each individual bit-rate selection algorithm in the mobile-fixed WiFi network.

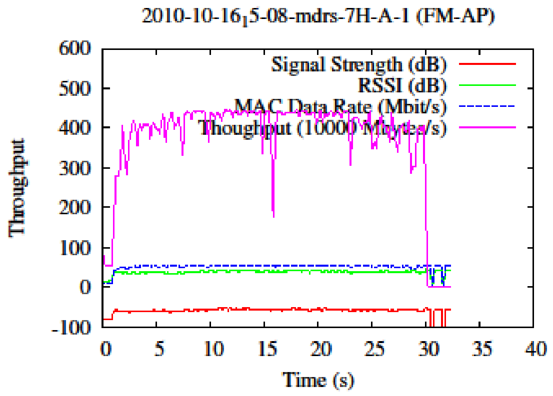
A.3.1 AP

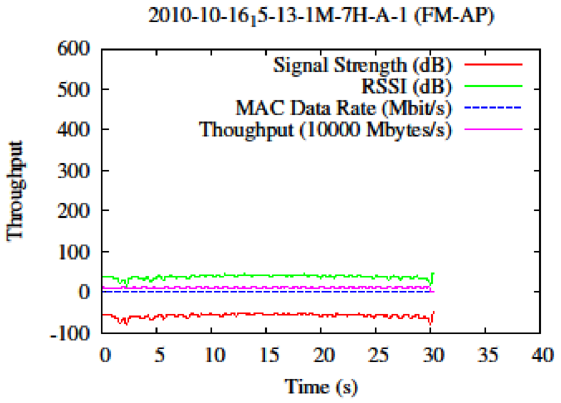


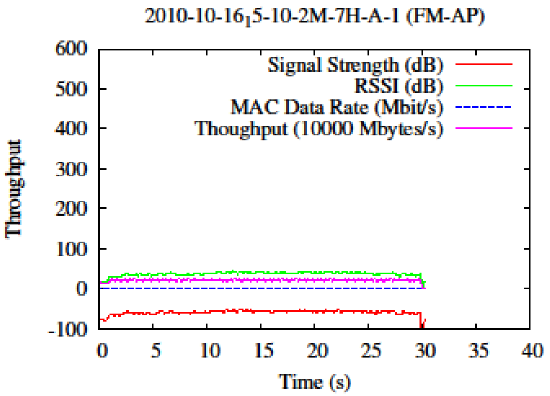


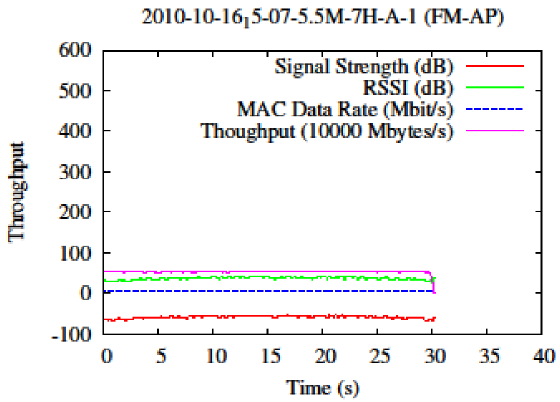


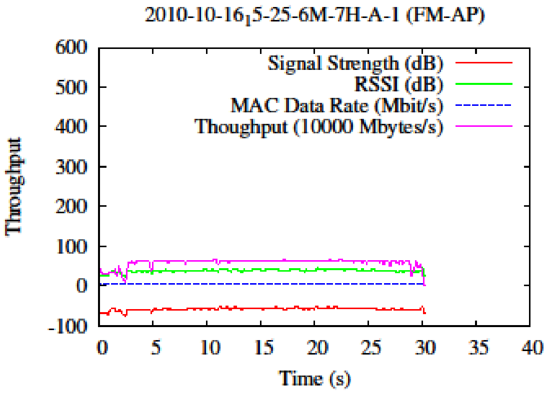


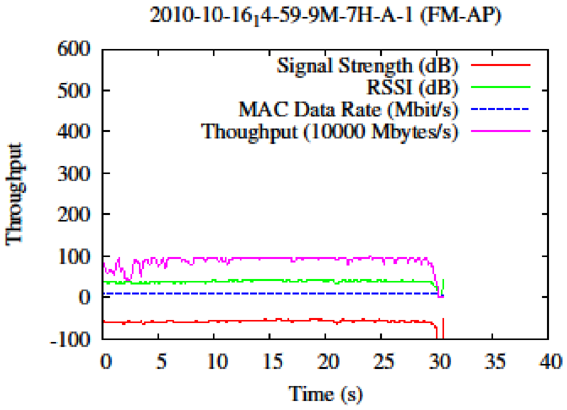


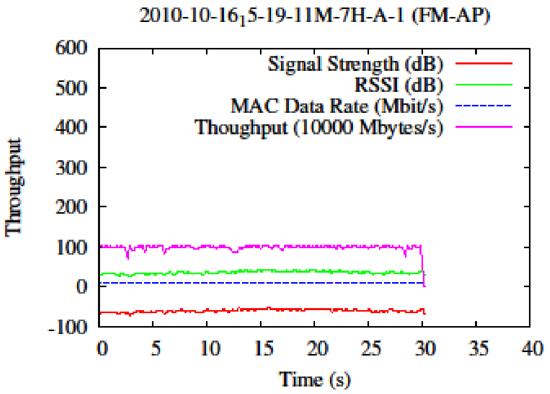


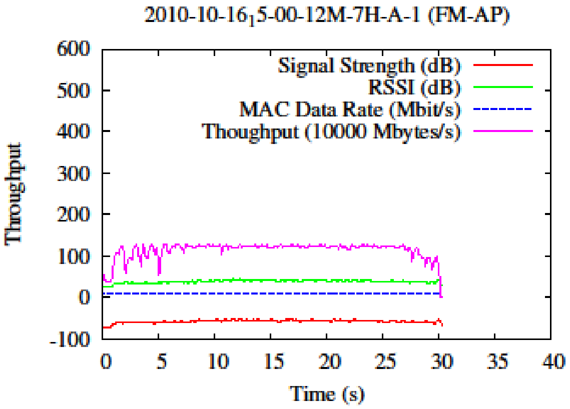

2010-10-16$_1$5-10-2M-7H-A-1 (FM-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Mbytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

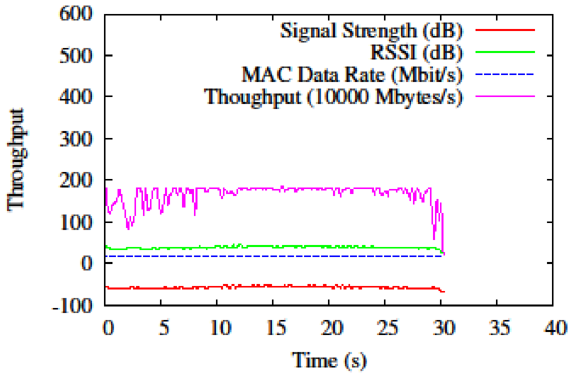

2010-10-16$_1$5-07-5.5M-7H-A-1 (FM-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Mbytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

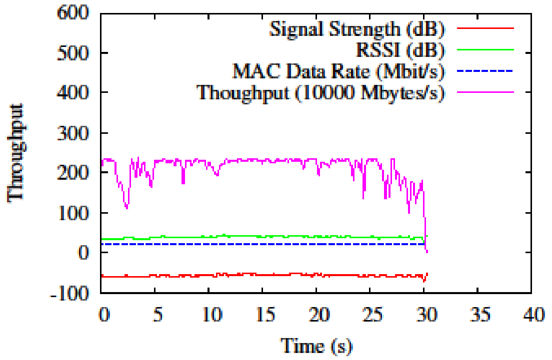

2010-10-16$_1$5-25-6M-7H-A-1 (FM-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Mbytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

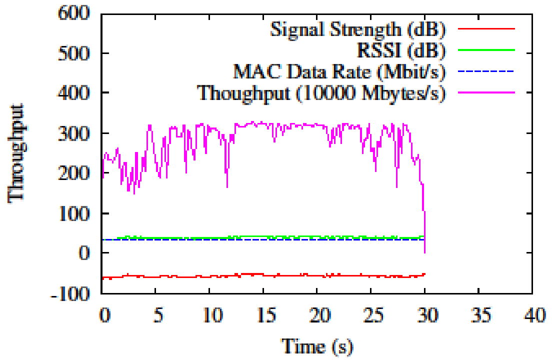

2010-10-16$_1$4-59-9M-7H-A-1 (FM-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Mbytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

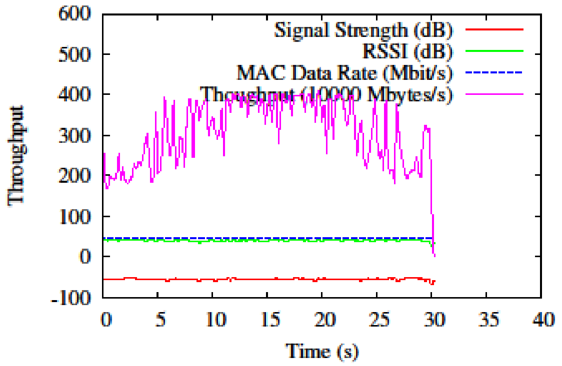

2010-10-16$_1$5-19-11M-7H-A-1 (FM-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Mbytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

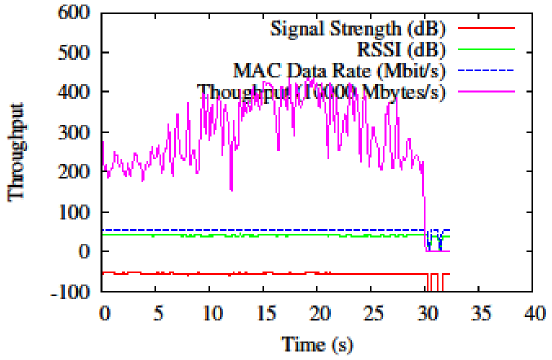

2010-10-16$_1$5-00-12M-7H-A-1 (FM-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Mbytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)


2010-10-16$_1$5-02-18M-7H-A-1 (FM-AP)

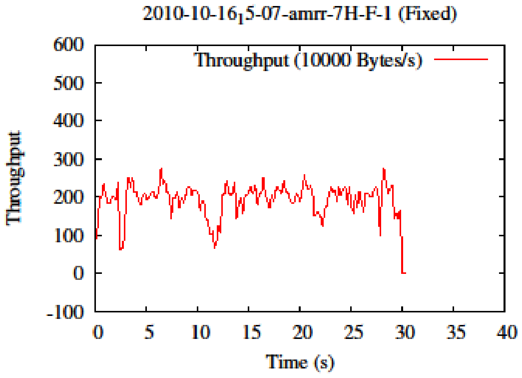

2010-10-16$_1$5-11-24M-7H-A-1 (FM-AP)

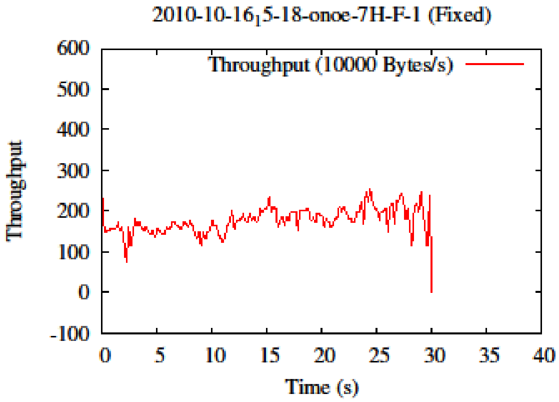

2010-10-16$_1$5-15-36M-7H-A-1 (FM-AP)

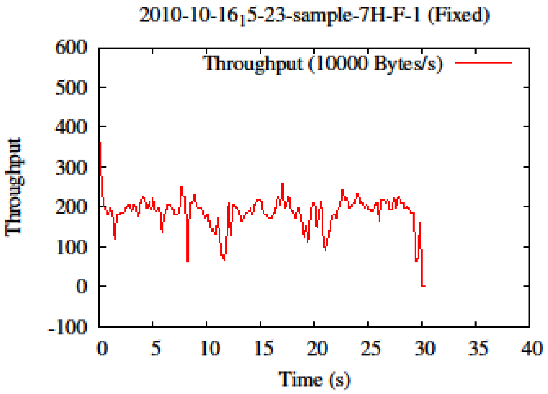

2010-10-16$_1$5-03-48M-7H-A-1 (FM-AP)

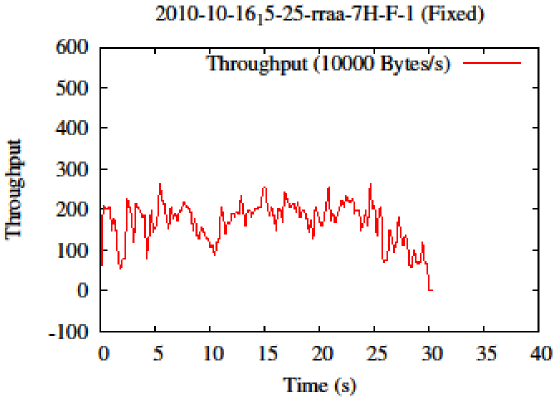

2010-10-16$_1$5-18-54M-7H-A-1 (FM-AP)

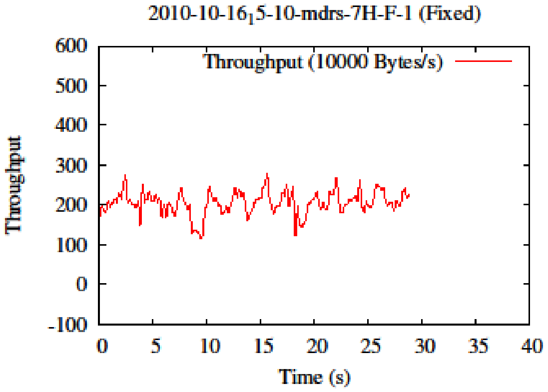
A.3.2 Fixed WiFi Client

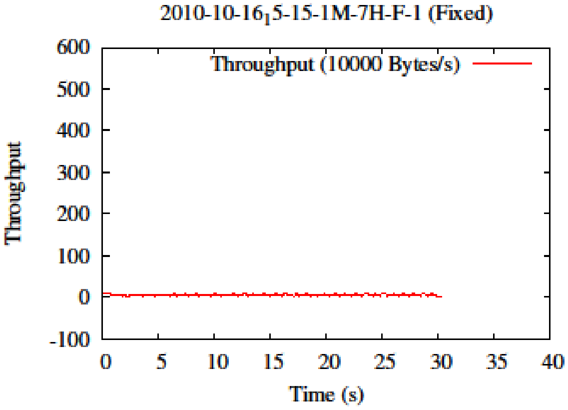


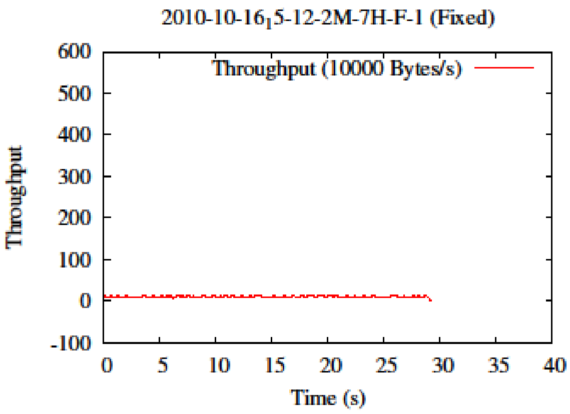


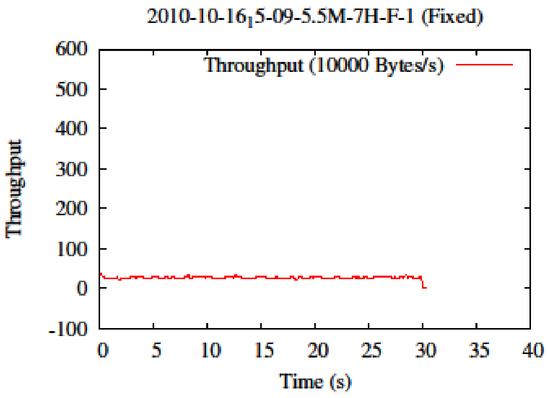


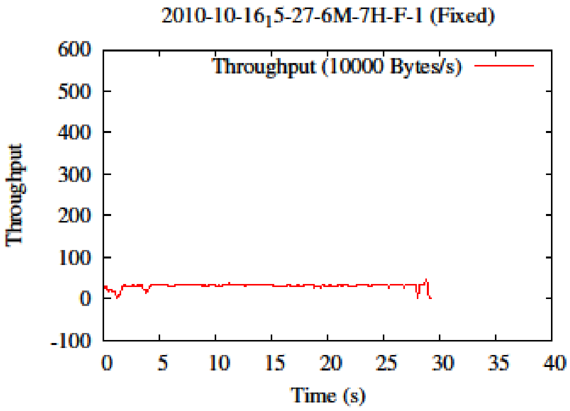


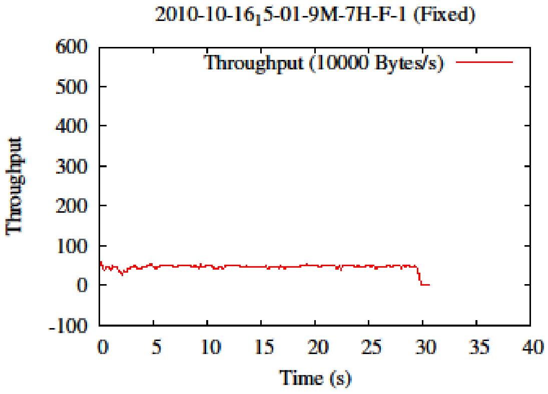


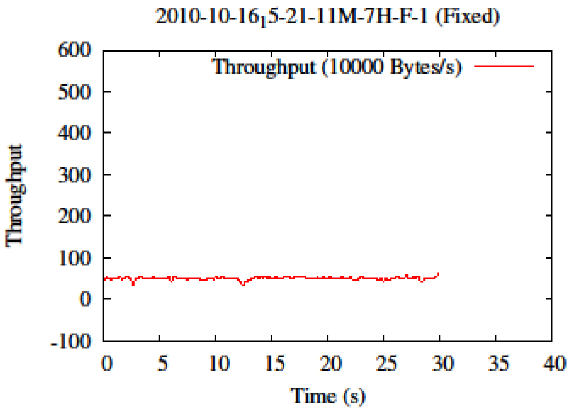


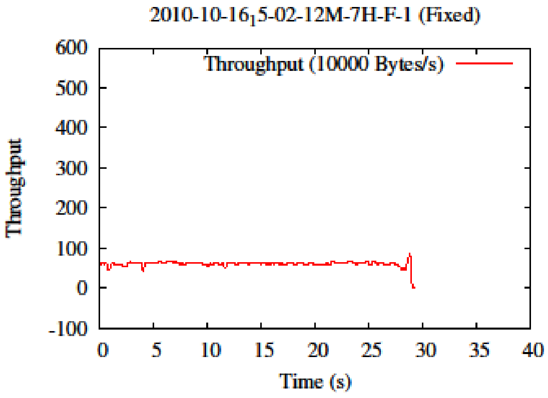

2010-10-16$_1$5-12-2M-7H-F-1 (Fixed)
Throughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

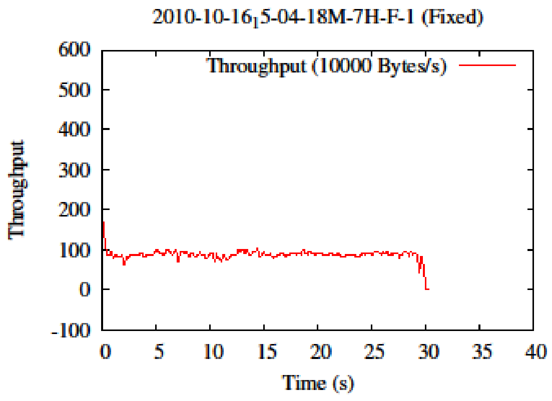

2010-10-16$_1$5-09-5.5M-7H-F-1 (Fixed)
Throughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

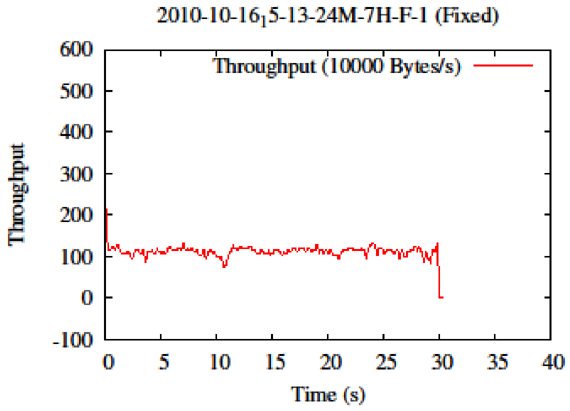

2010-10-16$_1$5-27-6M-7H-F-1 (Fixed)
Throughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

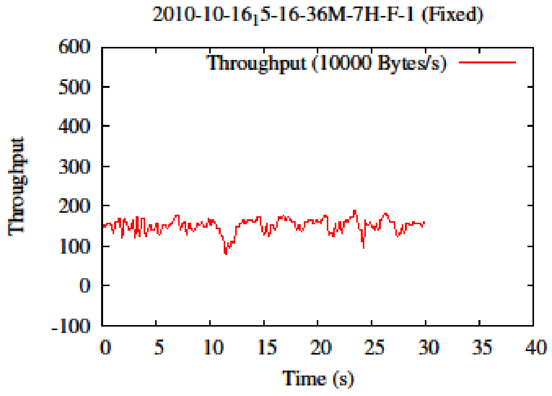

2010-10-16$_1$5-01-9M-7H-F-1 (Fixed)
Throughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

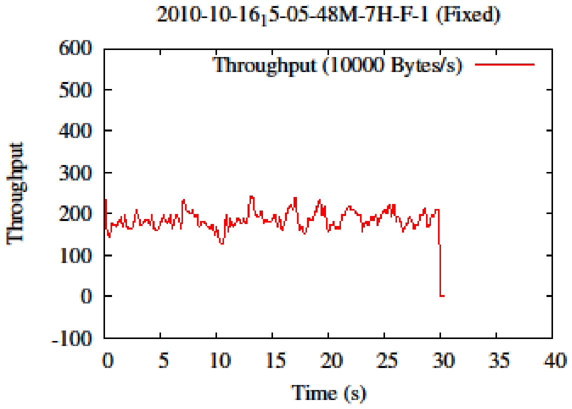

2010-10-16$_1$5-21-11M-7H-F-1 (Fixed)
Throughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

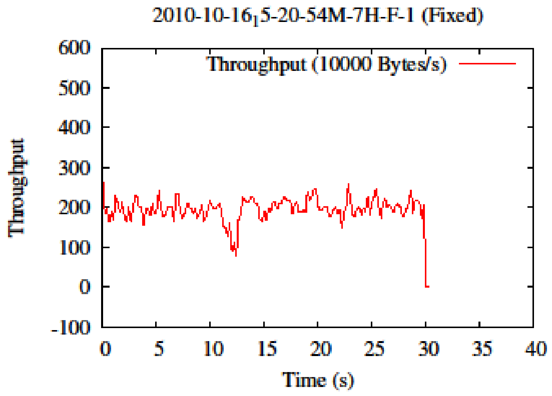

2010-10-16$_1$5-02-12M-7H-F-1 (Fixed)
Throughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

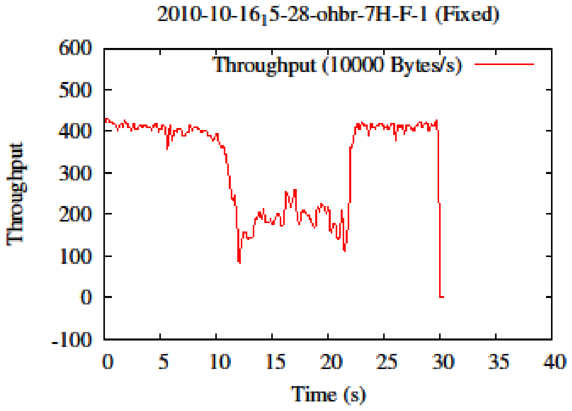

2010-10-16$_1$5-04-18M-7H-F-1 (Fixed)


2010-10-16$_1$5-13-24M-7H-F-1 (Fixed)


2010-10-16$_1$5-16-36M-7H-F-1 (Fixed)

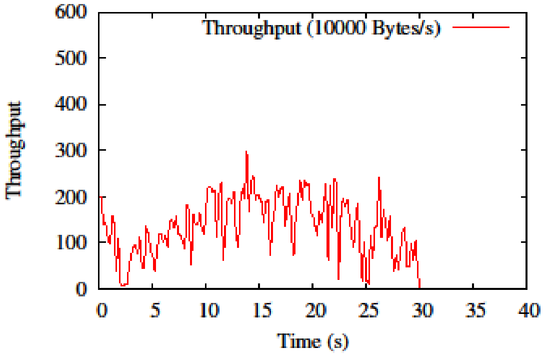

2010-10-16$_1$5-05-48M-7H-F-1 (Fixed)


2010-10-16$_1$5-20-54M-7H-F-1 (Fixed)

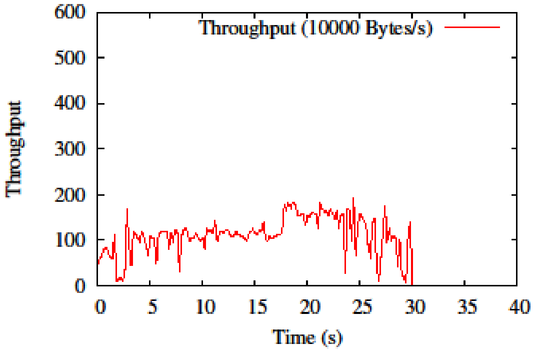

2010-10-16$_1$5-28-ohbr-7H-F-1 (Fixed)

A.3.3 Vehicular WiFi Client

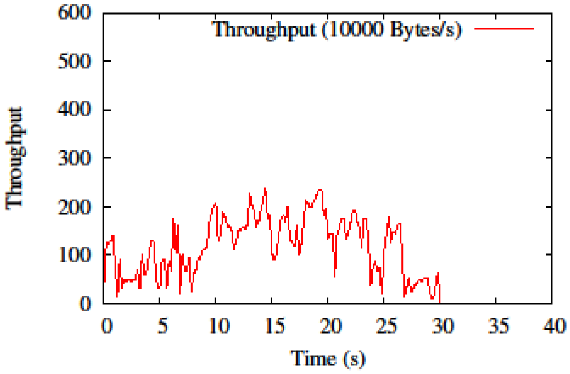
2010-10-16$_1$4-59-amrr-7H-M-1 (Atheros, Mobile)



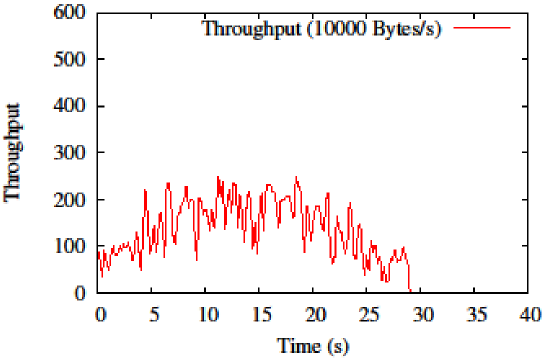
2010-10-16$_1$5-10-onoe-7H-M-1 (Atheros, Mobile)



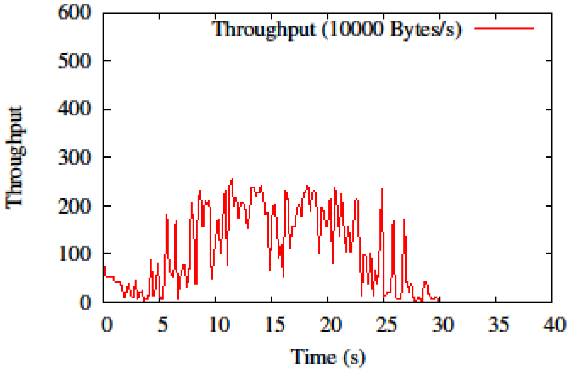
2010-10-16$_1$5-15-sample-7H-M-1 (Atheros, Mobile)



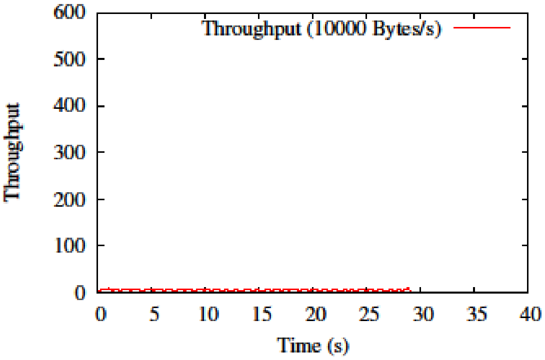
2010-10-16$_1$5-17-rraa-7H-M-1 (Atheros, Mobile)

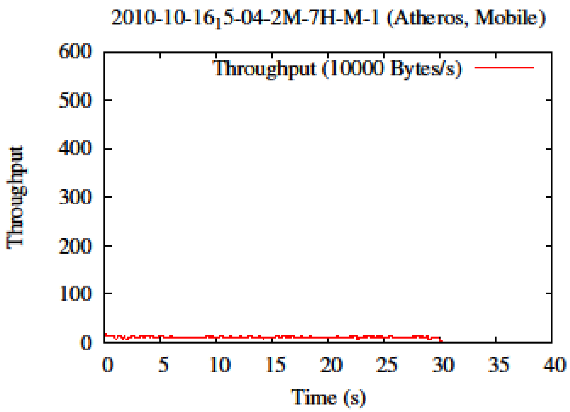


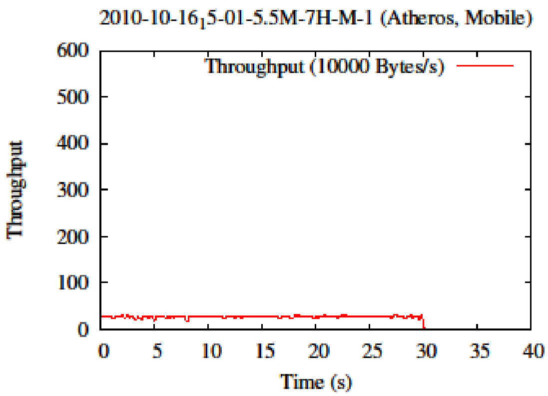
2010-10-16$_1$5-02-mdrs-7H-M-1 (Atheros, Mobile)

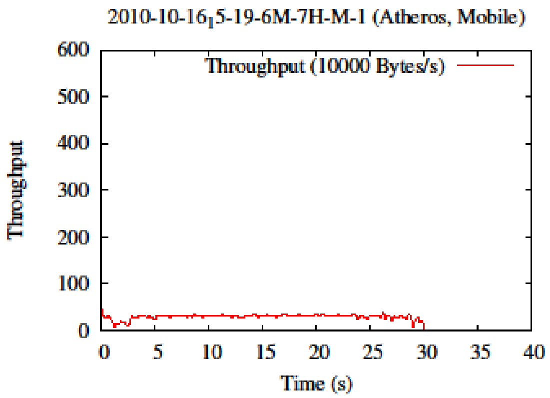


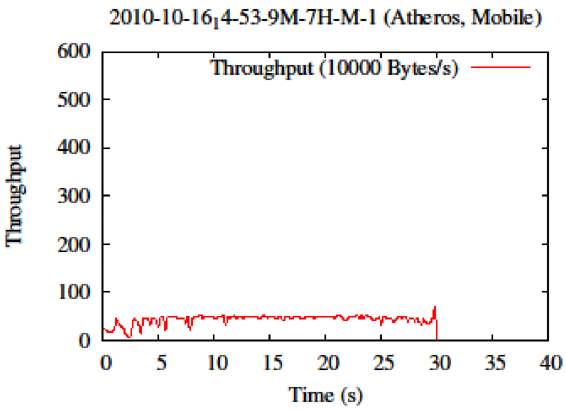
2010-10-16$_1$5-07-1M-7H-M-1 (Atheros, Mobile)

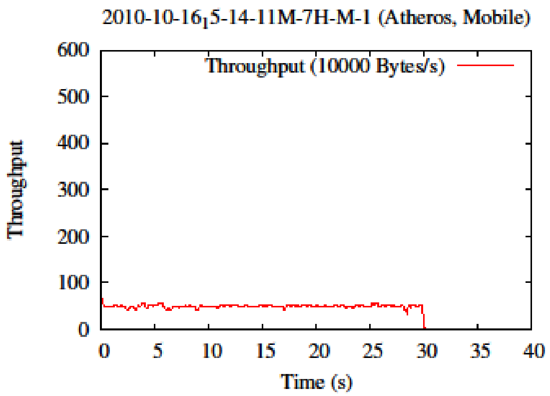


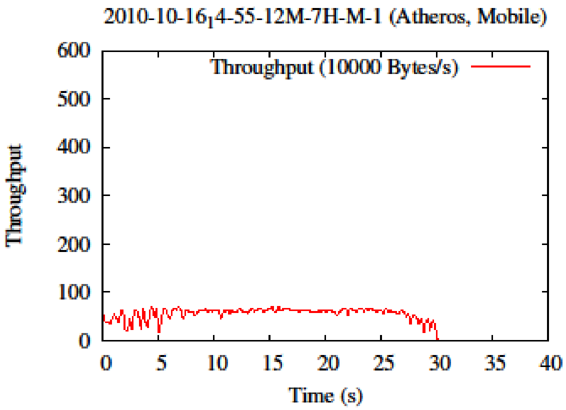

2010-10-16$_1$5-04-2M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
Time (s)
0
5
10
15
20
25
30
35
40

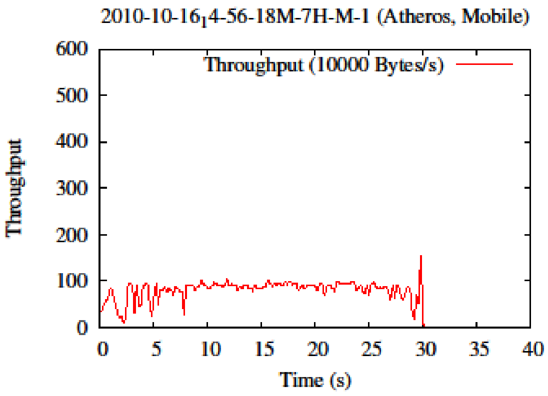

2010-10-16$_1$5-01-5.5M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
Time (s)
0
5
10
15
20
25
30
35
40

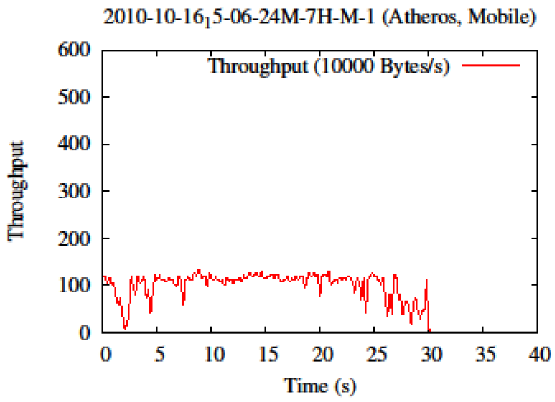

2010-10-16$_1$5-19-6M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
Time (s)
0
5
10
15
20
25
30
35
40

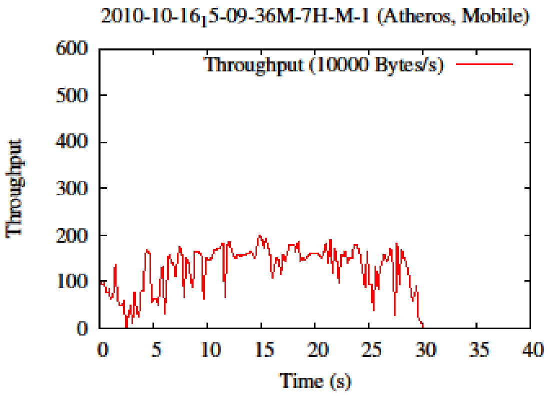

2010-10-16$_1$4-53-9M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
Time (s)
0
5
10
15
20
25
30
35
40

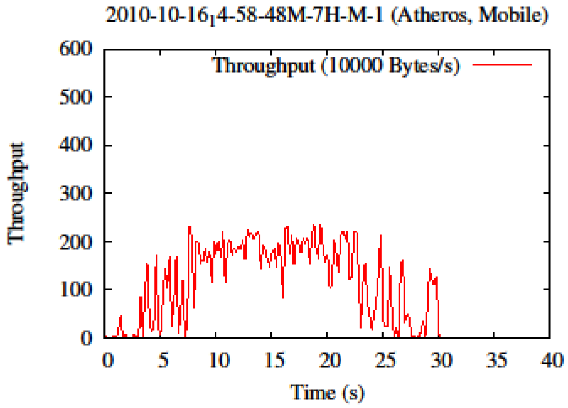

2010-10-16$_1$5-14-11M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
Time (s)
0
5
10
15
20
25
30
35
40

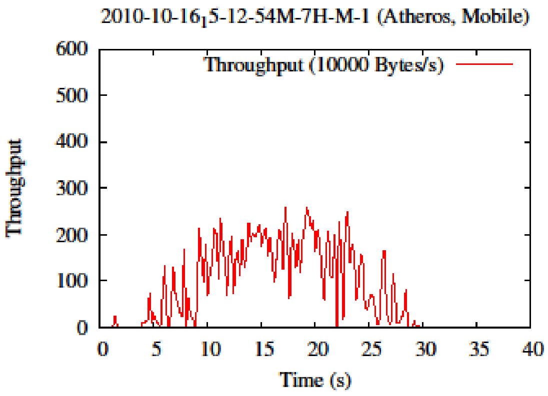

2010-10-16$_1$4-55-12M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
Time (s)
0
5
10
15
20
25
30
35
40

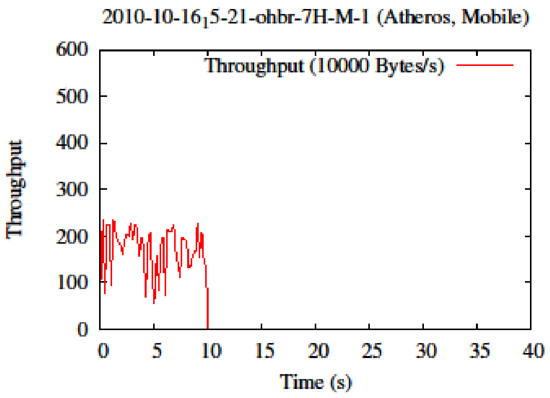

2010-10-16$_1$4-56-18M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)


2010-10-16$_1$5-06-24M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)


2010-10-16$_1$5-09-36M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)


2010-10-16$_1$4-58-48M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)

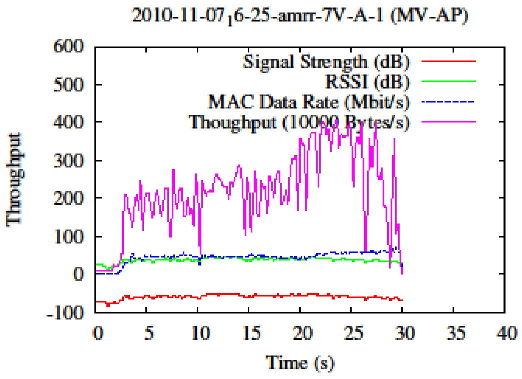

2010-10-16$_1$5-12-54M-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)

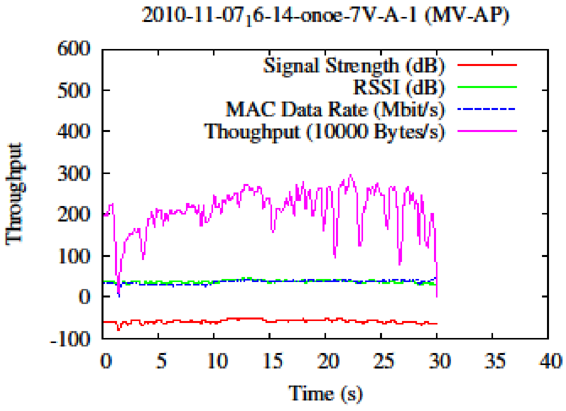

2010-10-16$_1$5-21-ohbr-7H-M-1 (Atheros, Mobile)
Throughput (10000 Bytes/s)
Throughput
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)

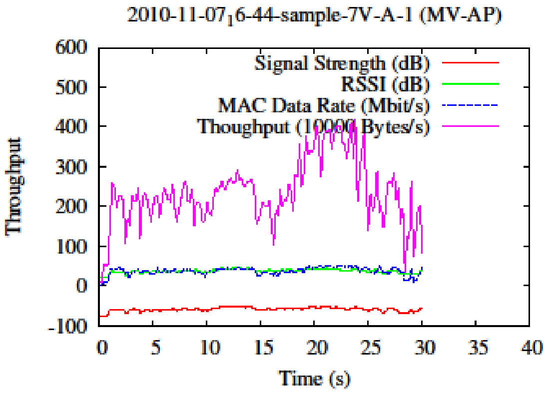
A.4 Multi-Vehicular WiFi Network

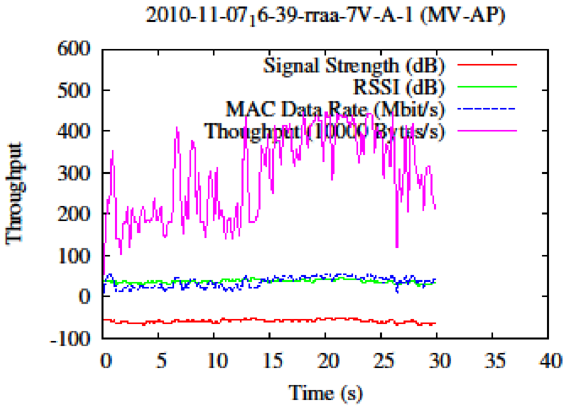
The following diagrams depict the data transfer progress for each individual bit-rate selection algorithm in the multi-vehicular WiFi network.

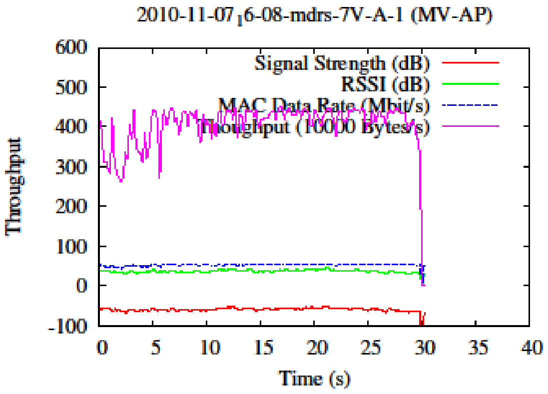
A.4.1 AP

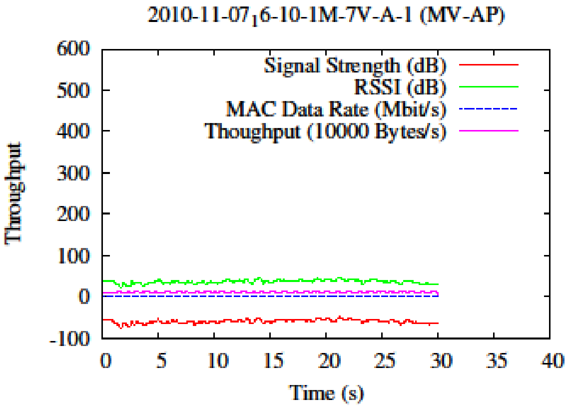

2010-11-07$_1$6-25-amrr-7V-A-1 (MV-AP)

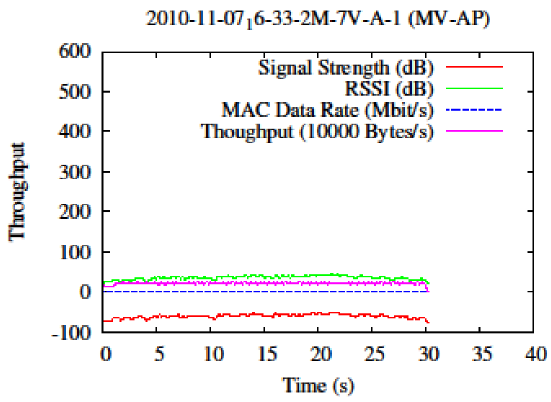

2010-11-07$_1$6-14-onoe-7V-A-1 (MV-AP)

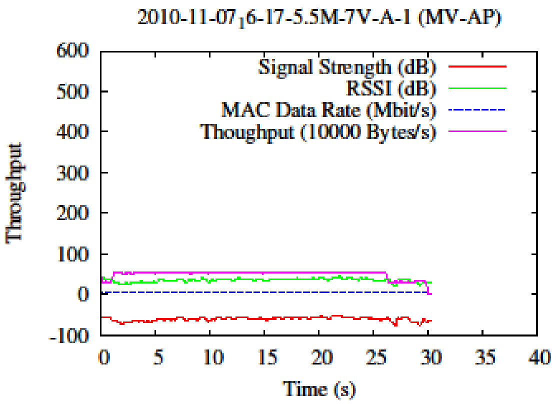

2010-11-07$_1$6-44-sample-7V-A-1 (MV-AP)

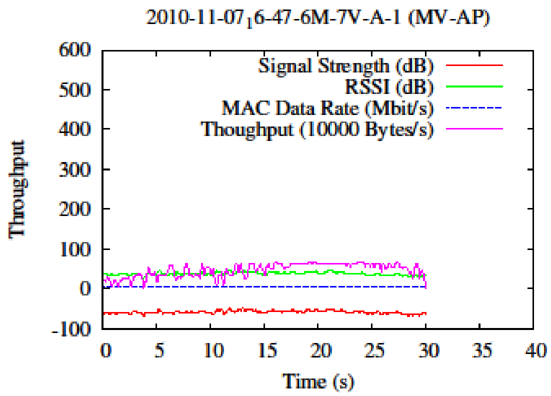

2010-11-07$_1$6-39-rraa-7V-A-1 (MV-AP)

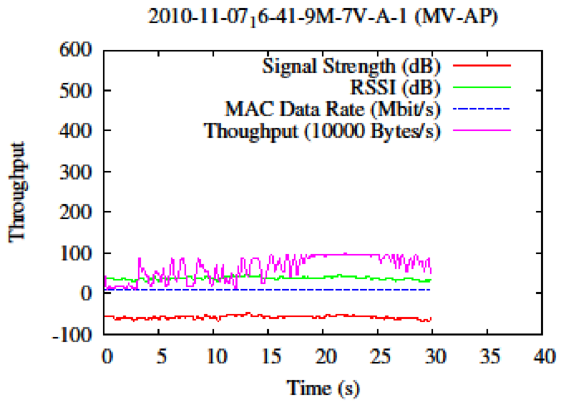

2010-11-07$_1$6-08-mdrs-7V-A-1 (MV-AP)

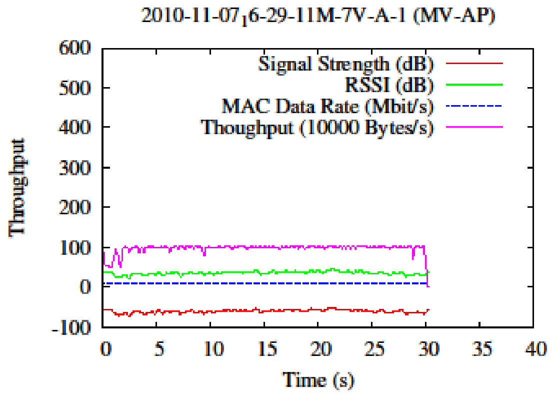

2010-11-07$_1$6-10-1M-7V-A-1 (MV-AP)

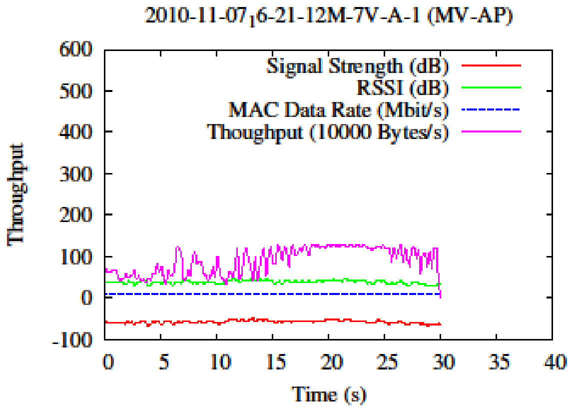

2010-11-07$_1$6-33-2M-7V-A-1 (MV-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

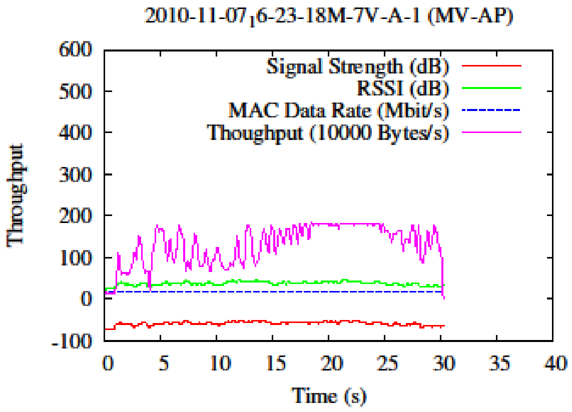

2010-11-07$_1$6-17-5.5M-7V-A-1 (MV-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

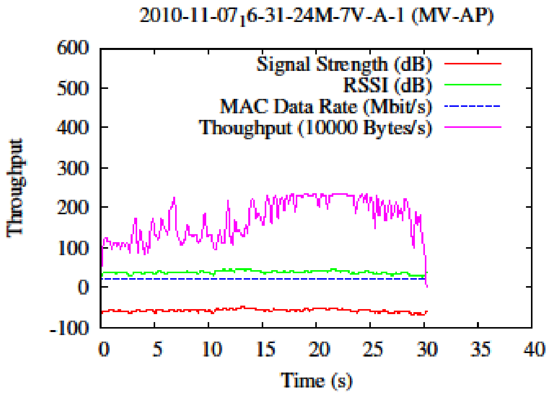

2010-11-07$_1$6-47-6M-7V-A-1 (MV-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

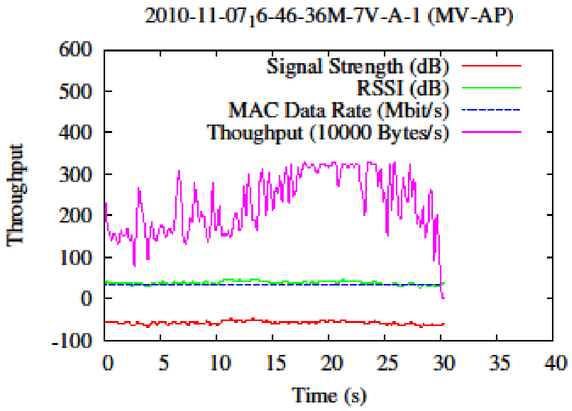

2010-11-07$_1$6-41-9M-7V-A-1 (MV-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

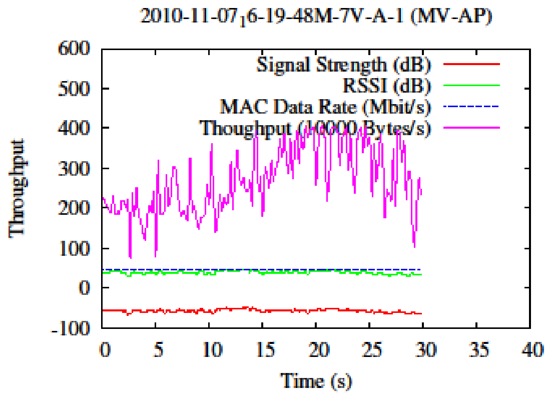

2010-11-07$_1$6-29-11M-7V-A-1 (MV-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

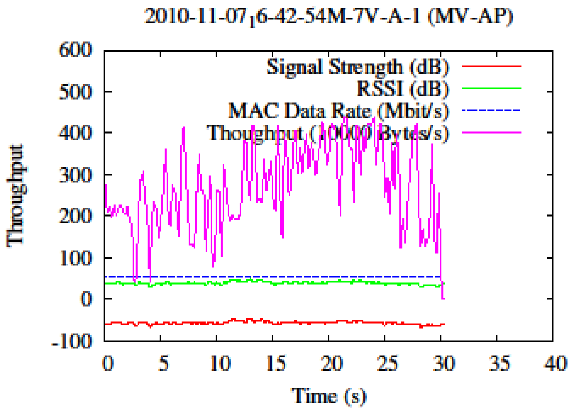

2010-11-07$_1$6-21-12M-7V-A-1 (MV-AP)
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
Throughput
600
500
400
300
200
100
0
-100
0
5
10
15
20
25
30
35
40
Time (s)

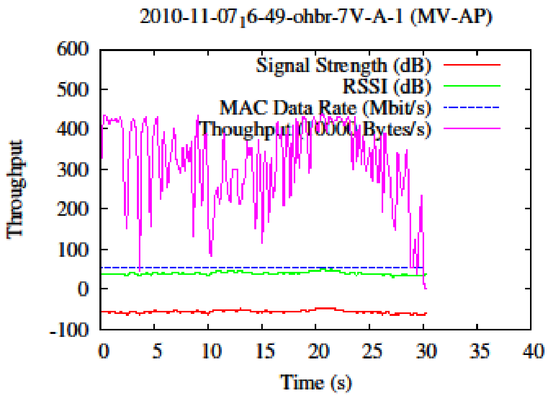

2010-11-07$_1$6-23-18M-7V-A-1 (MV-AP)
Throughput
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
600
500
400
300
200
100
0
-100
0 5 10 15 20 25 30 35 40
Time (s)


2010-11-07$_1$6-31-24M-7V-A-1 (MV-AP)
Throughput
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
600
500
400
300
200
100
0
-100
0 5 10 15 20 25 30 35 40
Time (s)

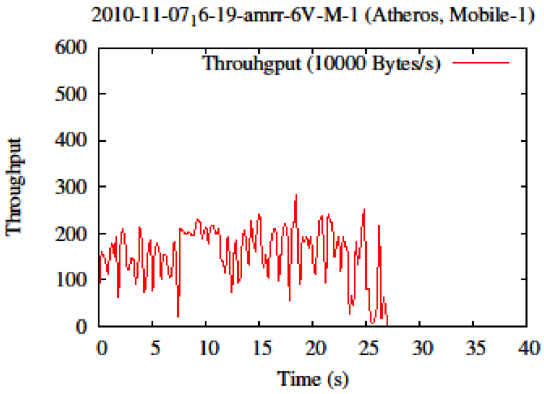

2010-11-07$_1$6-46-36M-7V-A-1 (MV-AP)
Throughput
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
600
500
400
300
200
100
0
-100
0 5 10 15 20 25 30 35 40
Time (s)

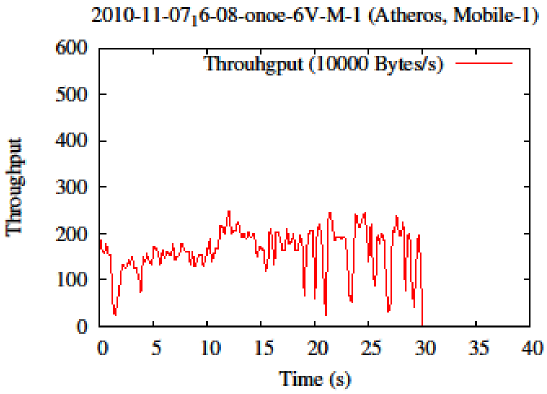

2010-11-07$_1$6-19-48M-7V-A-1 (MV-AP)
Throughput
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
600
500
400
300
200
100
0
-100
0 5 10 15 20 25 30 35 40
Time (s)

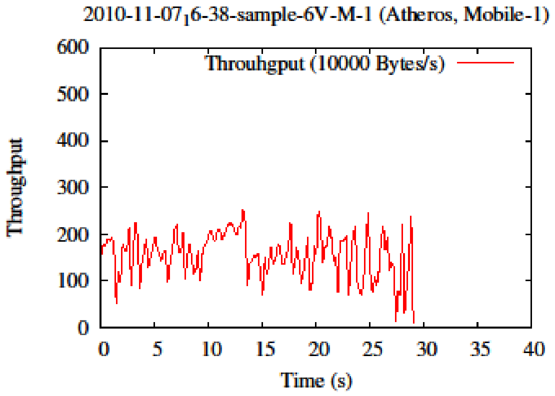

2010-11-07$_1$6-42-54M-7V-A-1 (MV-AP)
Throughput
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
600
500
400
300
200
100
0
-100
0 5 10 15 20 25 30 35 40
Time (s)

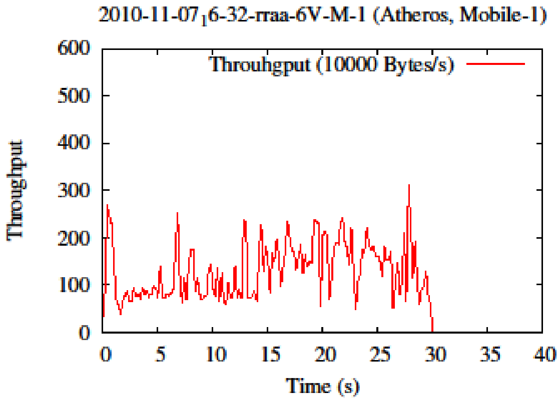

2010-11-07$_1$6-49-ohbr-7V-A-1 (MV-AP)
Throughput
Signal Strength (dB)
RSSI (dB)
MAC Data Rate (Mbit/s)
Thoughput (10000 Bytes/s)
600
500
400
300
200
100
0
-100
0 5 10 15 20 25 30 35 40
Time (s)

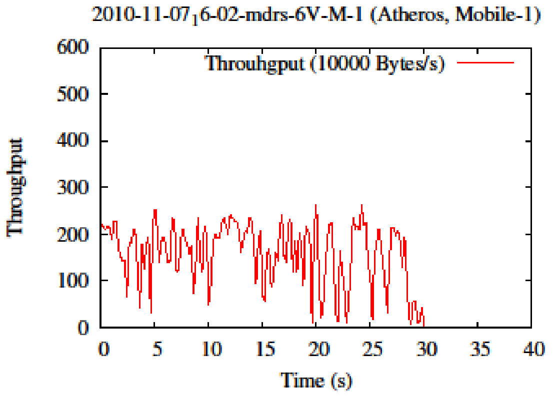
A.4.2 1st Vehicular WiFi Client

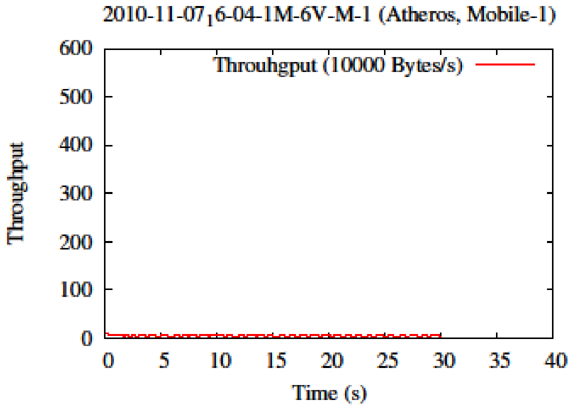




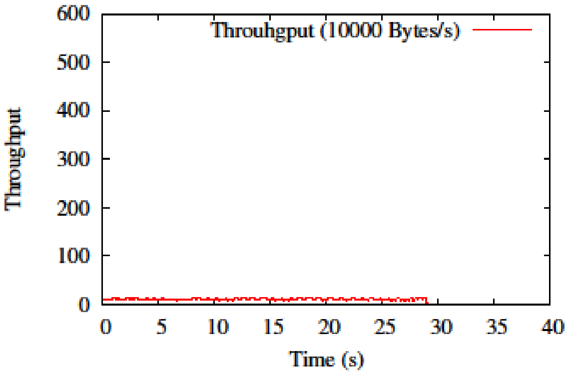




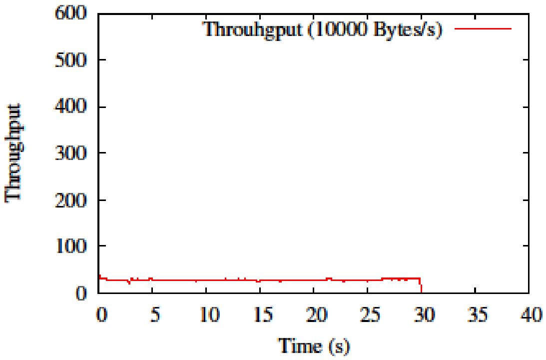




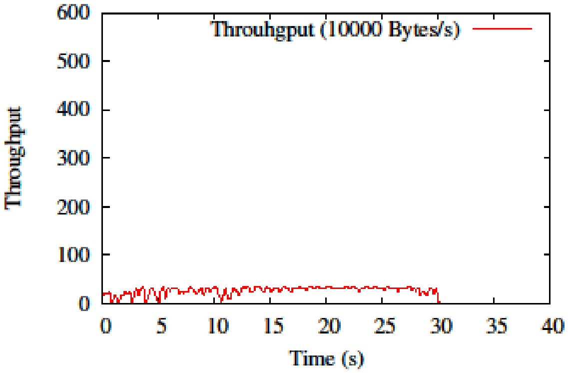
2010-11-07$_1$6-27-2M-6V-M-1 (Atheros, Mobile-1)



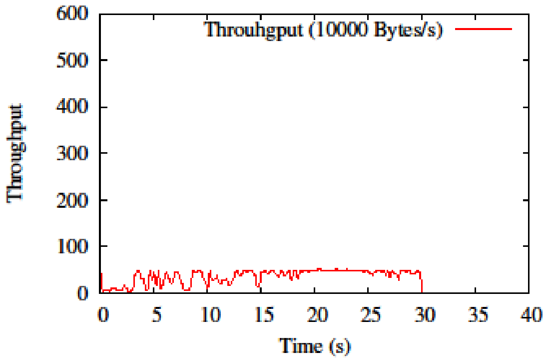
2010-11-07$_1$6-11-5.5M-6V-M-1 (Atheros, Mobile-1)



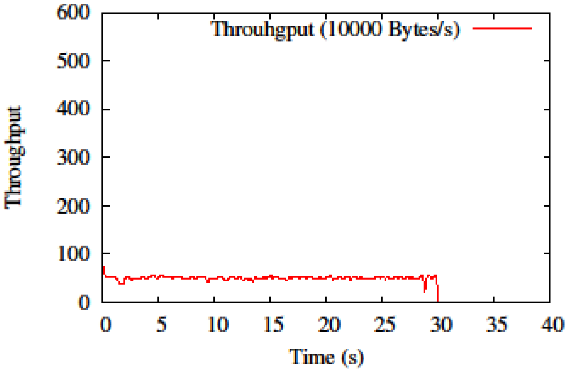
2010-11-07$_1$6-41-6M-6V-M-1 (Atheros, Mobile-1)



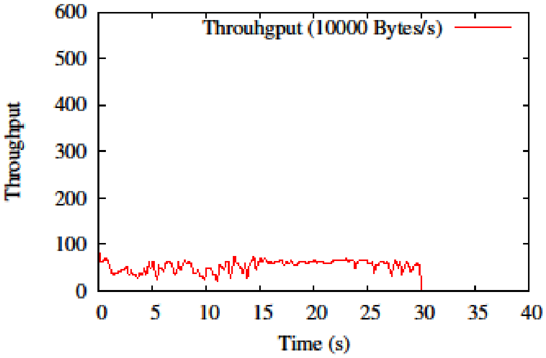
2010-11-07$_1$6-35-9M-6V-M-1 (Atheros, Mobile-1)

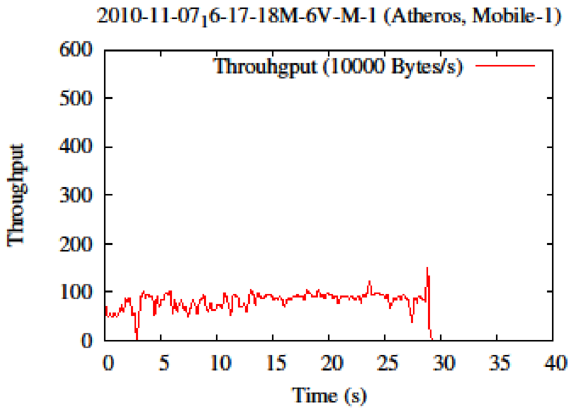


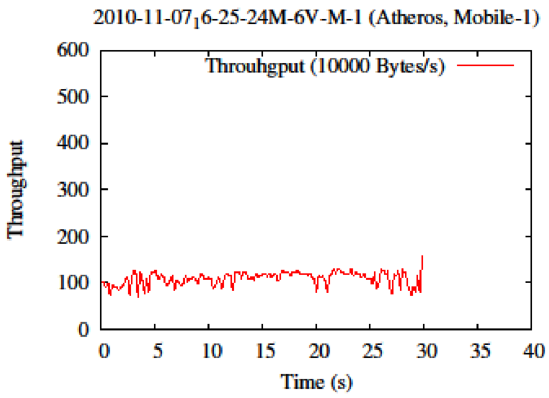
2010-11-07$_1$6-23-11M-6V-M-1 (Atheros, Mobile-1)

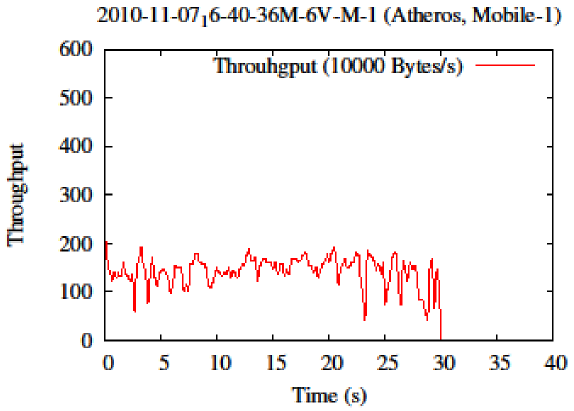


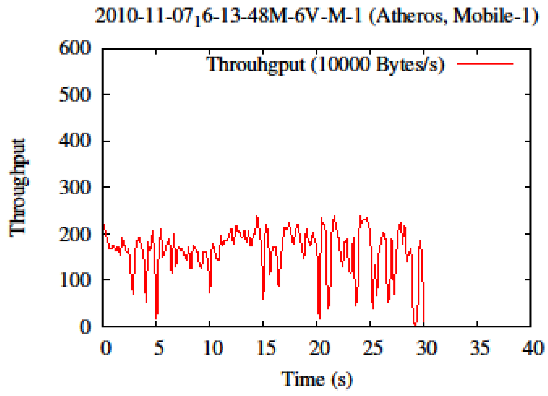
2010-11-07$_1$6-15-12M-6V-M-1 (Atheros, Mobile-1)

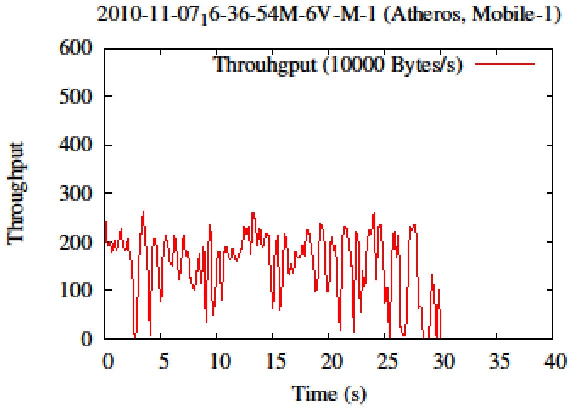


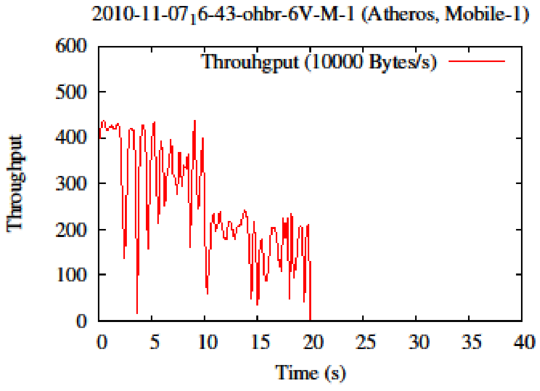

2010-11-07$_1$6-17-18M-6V-M-1 (Atheros, Mobile-1)
Throughput
Throuhgput (10000 Bytes/s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)


2010-11-07$_1$6-25-24M-6V-M-1 (Atheros, Mobile-1)
Throughput
Throuhgput (10000 Bytes/s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)


2010-11-07$_1$6-40-36M-6V-M-1 (Atheros, Mobile-1)
Throughput
Throuhgput (10000 Bytes/s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)

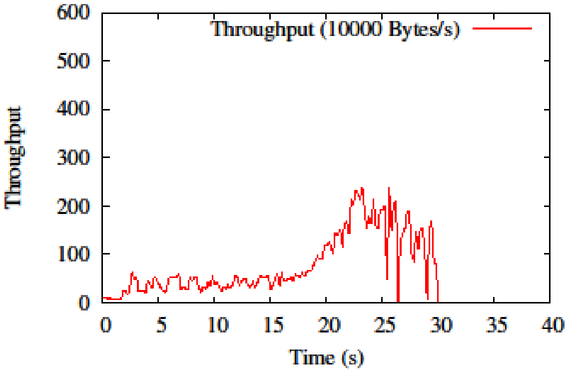

2010-11-07$_1$6-13-48M-6V-M-1 (Atheros, Mobile-1)
Throughput
Throuhgput (10000 Bytes/s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)


2010-11-07$_1$6-36-54M-6V-M-1 (Atheros, Mobile-1)
Throughput
Throuhgput (10000 Bytes/s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)

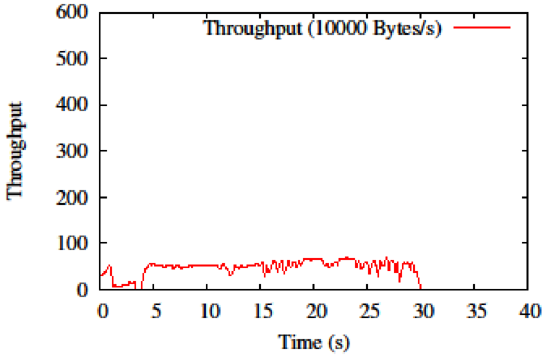

2010-11-07$_1$6-43-ohbr-6V-M-1 (Atheros, Mobile-1)
Throughput
Throuhgput (10000 Bytes/s)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
Time (s)

A.4.3 2nd Vehicular WiFi Client

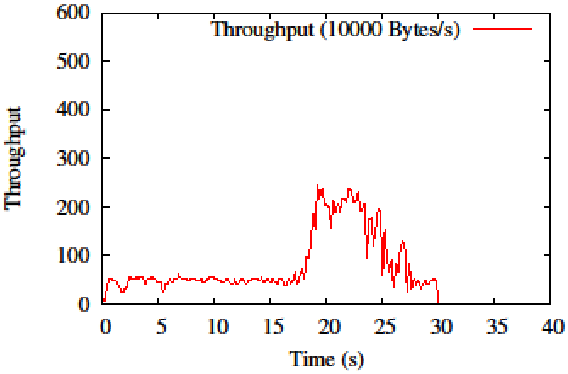
2010-11-07$_1$6-27-amrr-7V-F-1 (Athros, Mobile-2)



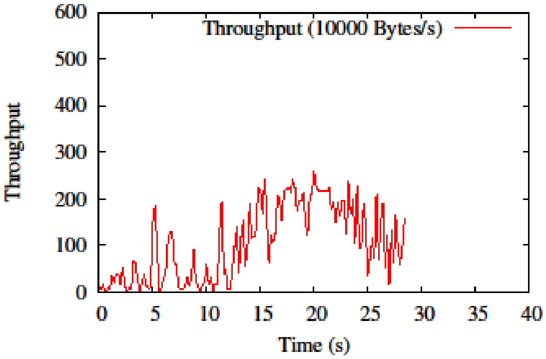
2010-11-07$_1$6-16-onoe-7V-F-1 (Athros, Mobile-2)



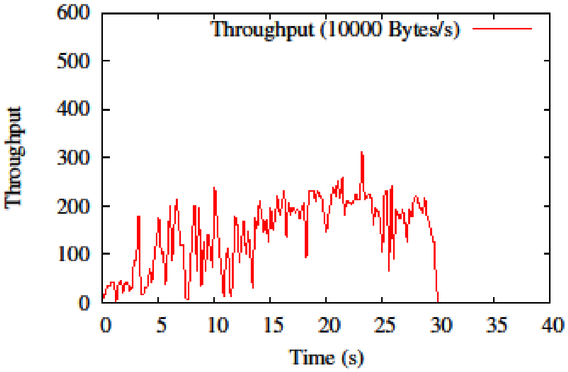
2010-11-07$_1$6-46-sample-7V-F-1 (Athros, Mobile-2)



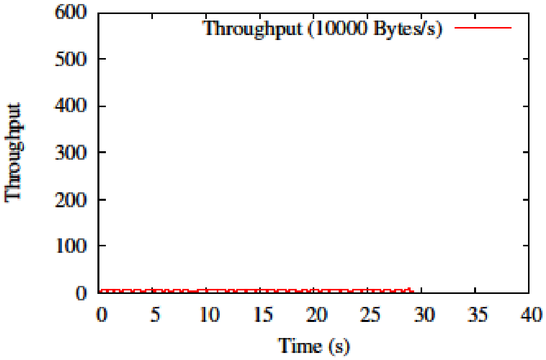
2010-11-07$_1$6-41-rraa-7V-F-1 (Athros, Mobile-2)

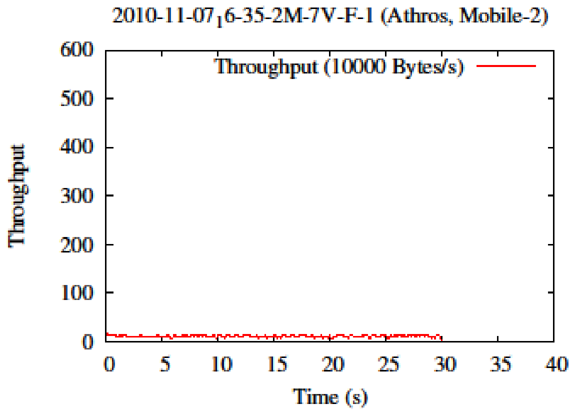


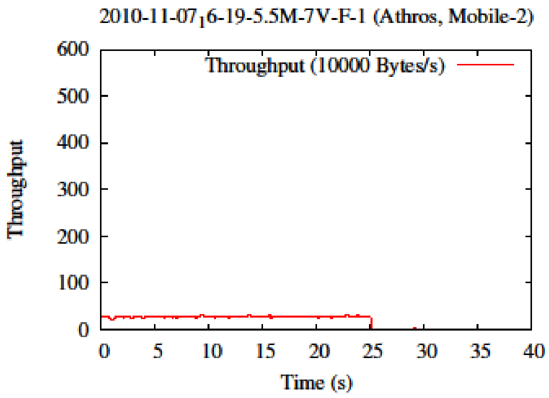
2010-11-07$_1$6-10-mdrs-7V-F-1 (Athros, Mobile-2)

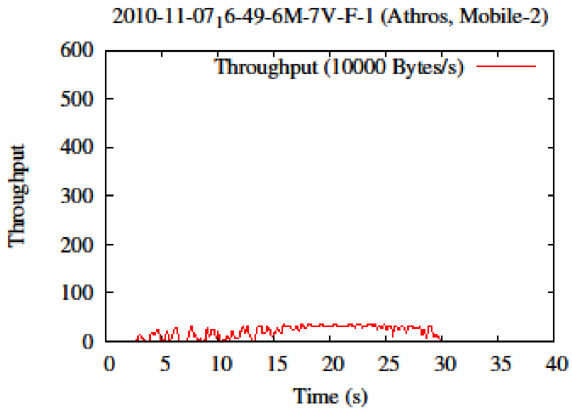


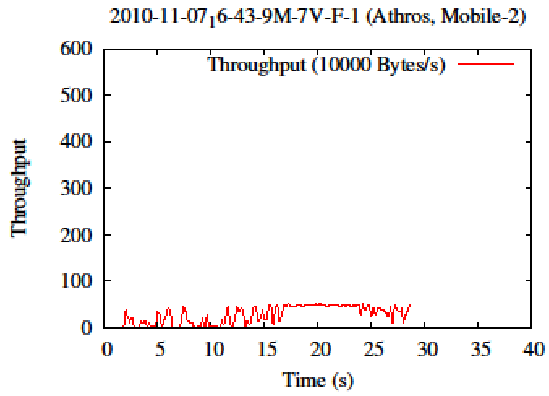
2010-11-07$_1$6-12-1M-7V-F-1 (Athros, Mobile-2)

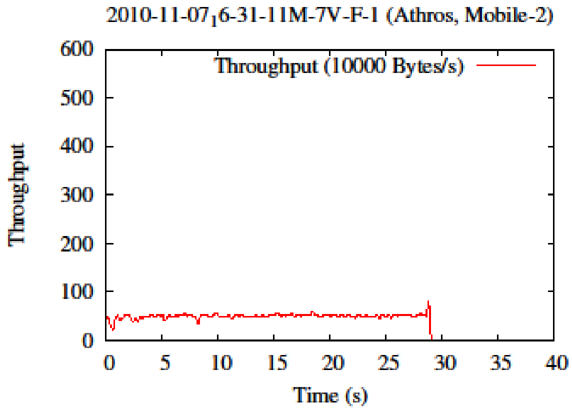


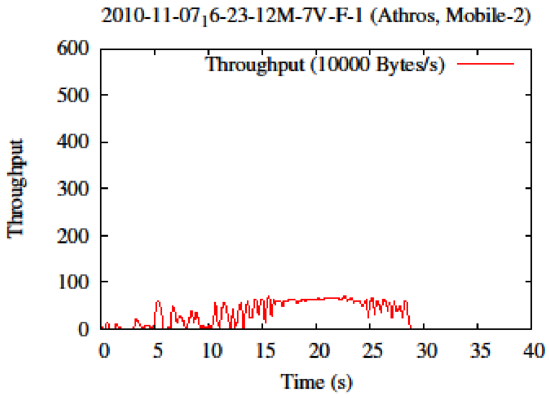

2010-11-07$_1$6-35-2M-7V-F-1 (Athros, Mobile-2)

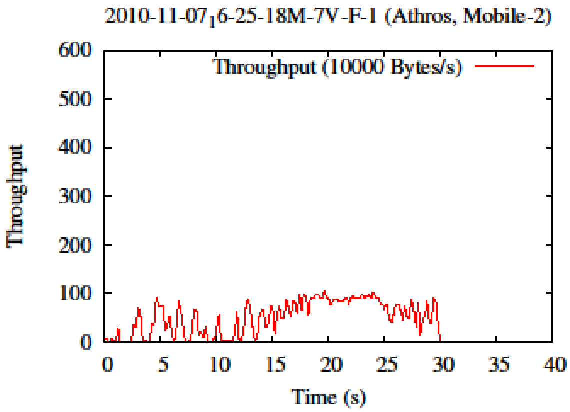

2010-11-07$_1$6-19-5.5M-7V-F-1 (Athros, Mobile-2)

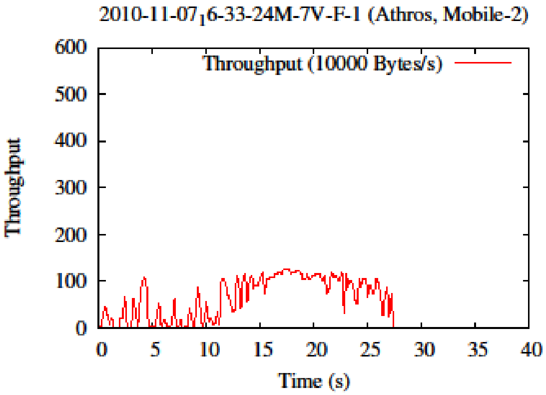

2010-11-07$_1$6-49-6M-7V-F-1 (Athros, Mobile-2)

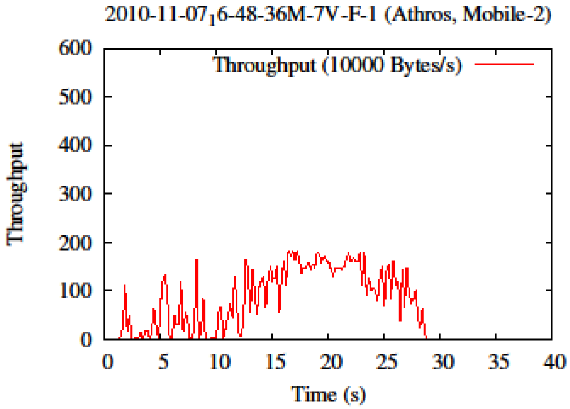

2010-11-07$_1$6-43-9M-7V-F-1 (Athros, Mobile-2)

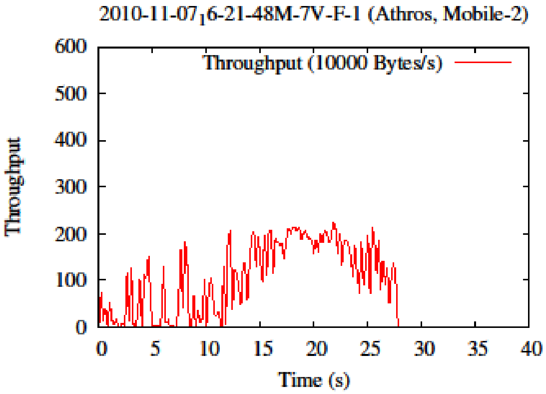

2010-11-07$_1$6-31-11M-7V-F-1 (Athros, Mobile-2)


2010-11-07$_1$6-23-12M-7V-F-1 (Athros, Mobile-2)


2010-11-07$_1$6-25-18M-7V-F-1 (Athros, Mobile-2)


2010-11-07$_1$6-33-24M-7V-F-1 (Athros, Mobile-2)


2010-11-07$_1$6-48-36M-7V-F-1 (Athros, Mobile-2)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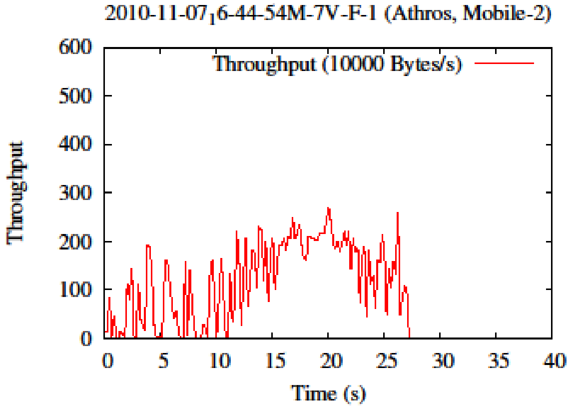
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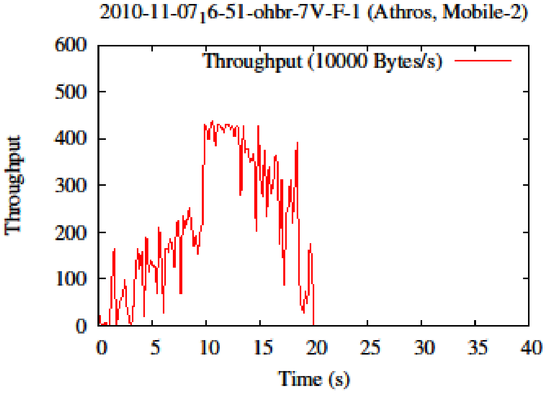
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