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Bandwidth Estimation using Passive Monitoring for WLANs

Case Study Report

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Bandwidth Estimation using Passive Monitoring for WLANs

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Abstract

Accurate bandwidth estimation plays vital role in traffic engineering and capacity planning support. In recent times, the focus is on Wireless Networks for bandwidth estimation via passively monitoring the channel by determining “busy” and “idle” periods. In this work, an effective bandwidth estimation technique using passive monitoring for a given Wireless link is performed for Wireless Meshed Network. Use and tuning of Kalman Filter parameters are investigated. Experimental comparisons of Kalman Filter have been made with Active Bandwidth Estimation tools for 802.11 based wireless networks. Impact of cross traffic interference and (802.11) rate-adaption on performance of developed method have been analyzed using single-hop.

1 Introduction

IEEE 802.11-based wireless mesh networks (WMNs) are being widely deployed in municipal and enterprise settings. Accurate bandwidth estimation is important for traffic engineering and capacity planning support such as providing QoS. Available bandwidth of a link relates to the unused or spare capacity of link during a given time period. It is determined by finding time period for which the link is not utilized for transmitting data. In such scenarios, providing performance guarantees to end users may be an important goal for the network administrators or ISPs. Admission control and routing schemes based on available bandwidth (Av-Bw) can be very effective for provisioning Quality of Service (QoS) to end users. However, WMNs present several challenges to the bandwidth estimation process, such as interference, contention based MAC, and rate-adaptation feature of 802.11 protocols.

The objective of this study is to implement a passive monitoring tool that can estimate channel utilization on a single-hop by sniffing wireless channel. Atheros based cards provide a simple mechanism to get information on “Channel Busy Time”. Having information on busy time allows calculating available bandwidth of a link by taking into account the efficiency of the WLAN protocol using e.g. the Bianchi model [1]. Better improvement of the bandwidth estimation is done using Kalman Filter (KF) Technique [2]. The developed tool has been evaluated by varying physical data rate, and amount of interference to identify the impact on the process of estimating Av-Bw in WMNs. This tool is compared against active probe-based tools such as Pathload and Abing. The contention based MAC, and the tendency of 802.11 protocols to provide fairness, likely cause these active tools to provide inaccurate estimates.

2 Related Work

The performance of probe-based tools for estimating Av-Bw in wired networks has been widely evaluated. However, performance of these tools for wireless networks has not been evaluated extensively. Even though it has been widely cited that these tools do not work well for wireless networks [3] [4], their performance has not been quantified via detailed experiments. Several recent works have also being proposed using a passive approach for bandwidth estimation in wireless networks. However, these approaches have mostly been tested via simulations only and lack an extensive experimental evaluation.

Basic purpose of using KF had been to improve the accuracy of the link capacity and bandwidth estimation. To obtain fast-tracking and accurate bandwidth estimates, KF needs to be tuned. This has been studied in several papers, for example in [2], [5]. However, [5] and [2] use active probing. Therefore, another goal is to tune the KF for the bandwidth estimate resulted from passive monitoring.

3 System Design

Consider 802.11 WLAN network, with RTS/CTS disabled. The following equation shows the total time involved in transmitting a packet:

$$TCSMA/CA = TDIFS + Tbackoff + TDATA + TSIFS + TACK \qquad (1)$$

For a given choice of protocol (802.11 a/b/g), all values are fixed, except for the back-off time and the data transmission time. The data transmission time *TDATA* depends on frame size and modulation rate (physical data rate) used. Idea behind passive scheme is for each node to monitor the channel and listen for ongoing packet transmissions. For each packet that a node hears, it calculates the total transmission time based on the frame size and data rate used to transmit the packet. Thus, each node can estimate the channel utilization (μ) and multiplying ($1 - \mu$) by capacity of the channel gives us an estimate of the available bandwidth as given in equation:

$$\text{Av-BW} = (1 - \mu) * C \qquad (2)$$

The maximum throughput capacity (C) of the channel can be estimated by using tools such as MGEN. In order to obtain this information on channel utilization (μ), the goal is to implement a monitoring module based on information available from the Linux kernel, using MADWIFI based wireless device driver. Using special registers (HW-register in card, ATH_BUSY 0x80f4 and ATH_BUSYCYCLE 0x80f8), the device driver can report information that allows to infer channel utilization μ within a given period.
Using channel utilization μ, the goal is to develop an effective bandwidth estimation tool using KF by passively monitoring and inspecting 'busy' and 'idle' periods of transmission channel.

3.1 Kalman Filter

The motivation behind using Kalman Filter (KF) for bandwidth estimation (Bw-Est), is that; with per-sample update of Bw-Est it is feasible to obtain instant indications of Av-Bw. Specifically it is useful for real-time congestion control mechanisms.

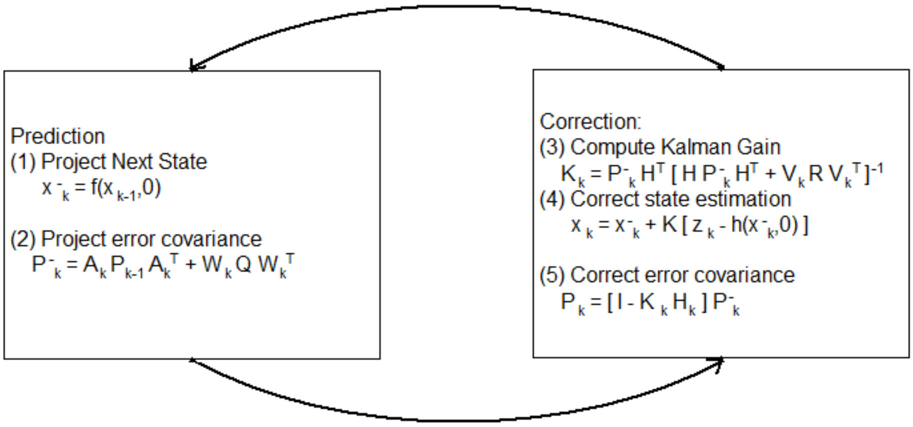


Figure 1: KF Feedback Cycle.

KF consists of continuous two-step Predictor-Corrector Estimation process that tracks state variables as shown in figure 1. Variables shown in figure 1 have following description:

x:	state estimate
z:	measurement data
A:	Jacobean of system model with respect to state noise
W:	Jacobean of the system model with respect to process noise
V:	Jacobean of measurement model with respect to measurement noise
H:	Jacobean of the measurement model
Q:	process noise covariance
R:	measurement noise covariance
K:	Kalman Gain
P:	estimated error covariance

In Prediction phase, next state x_k^- is predicted from current state x_{k-1}^- using state variables of system model. It is assumed that the model is perfect (i.e. no process noise W). Correction phase uses measurement data z_k to compute Kalman Gain K_k to minimize error covariance P_k. Next state estimation x_k^- is corrected by adding product of Kalman Gain K_k and prediction error to the prediction state x_k. Later error covariance estimation P_k is corrected using Kalman Gain K_k.

3.2 Extended KF for Bw-Est

KF has State vector x governed by equation

$$x_k = f(x_{k-1}, w_{k-1}) \qquad (3)$$

Here x_{k-1} is taken as Av-Bw (as given in eq.2). w_{k-1} is process noise p(w) ~ N(0,Q) (i.e. Q is process noise covariance) which is taken as 0 based on assumption that system is perfect. Measurement vector has following equation

$$z_k = f(x_k, v_k) \qquad (4)$$

Here v_k is measurement noise [p(v) ~ N(0, R)] where R is measurement noise covariance. KF has two tuning parameters for Bw-Est;

1. *Process Noise Covariance (Q)*
   It determines filter bandwidth i.e. how quickly KF can respond to changes in input signal. It is tuned during busy time measurement

2. *Measurement Noise Covariance (R)*
   It determines how filter responds to noise in input data. It is kept constant as 0.1.

4 KF Experiments for Bw-Est

Cross traffic of 1450 bytes/packet with the rate of 200packets/second is generated between two nodes 192.168.31.17 and 192.168.31.19. Physical data rates of nodes are incremented from 6Mbps till 24Mbps. Periodic, Poisson and Burst data transmissions are generated with measurement interval of 100ms and 1000ms to check estimation accuracy for Q = 0.1, 0.01 and 0.001.

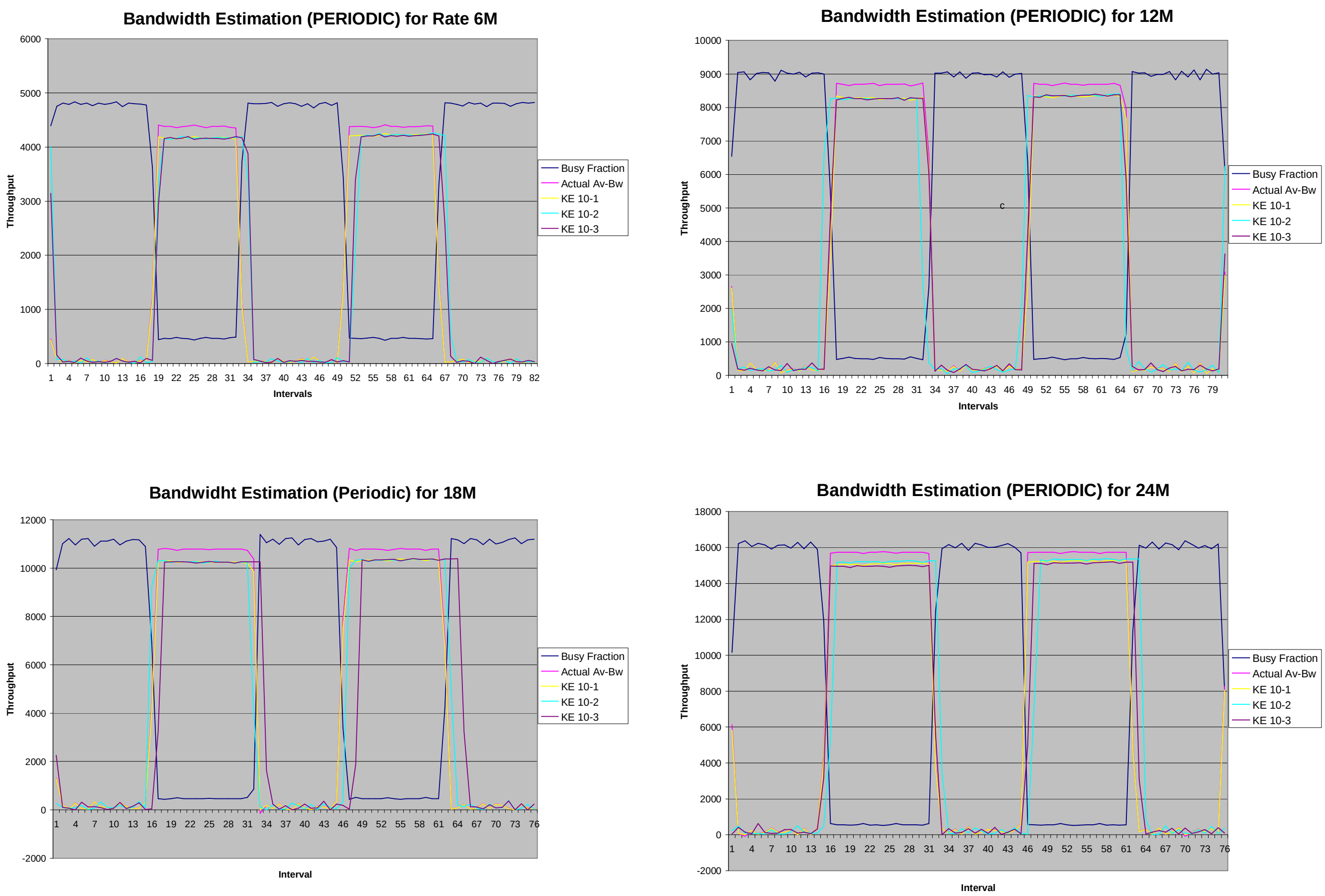
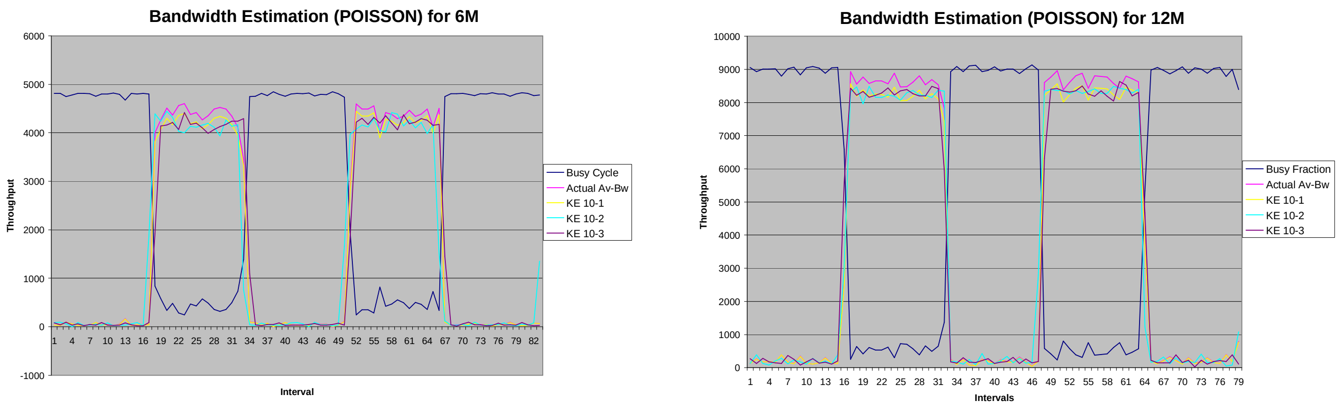


Figure 2: Av-Bw Estimation for Periodic Data with varying Physical rates to 6M, 12M, 18M and 24M.

Figure 2 displays KF estimation for Periodic data for incrementing physical rates respectively at measurement interval of 100ms. It is observed that KF with Q=0.1 produced the most accurate estimate. More experiments are performed using Poisson Data Transmission and Random Bursts with varying physical rates of nodes keeping same measurement interval. Figure 3 and 4 displays KF estimation for Poisson and Burst transmissions respectively.



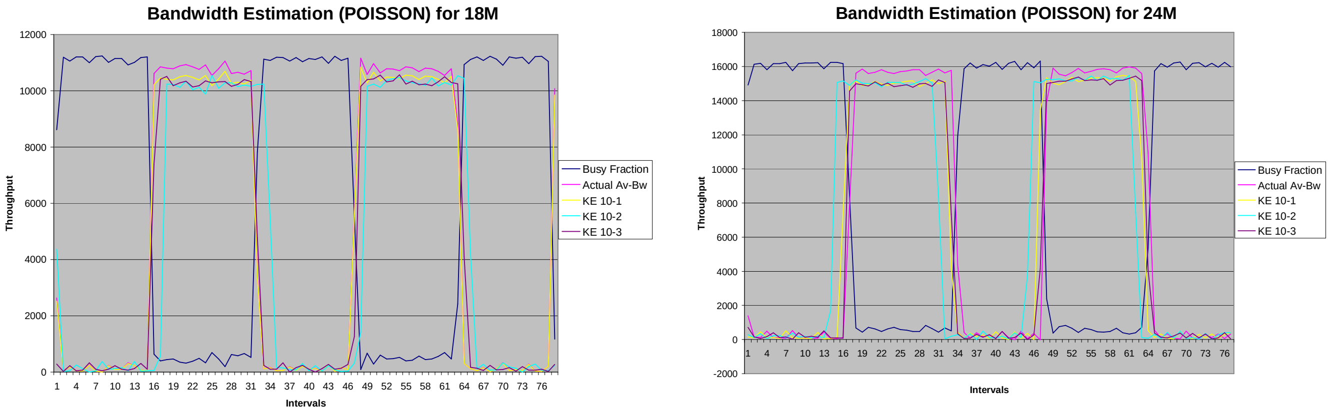


Figure 3: Av-Bw Estimation for Poisson Data with varying Physical rates to 6M, 12M, 18M and 24M.

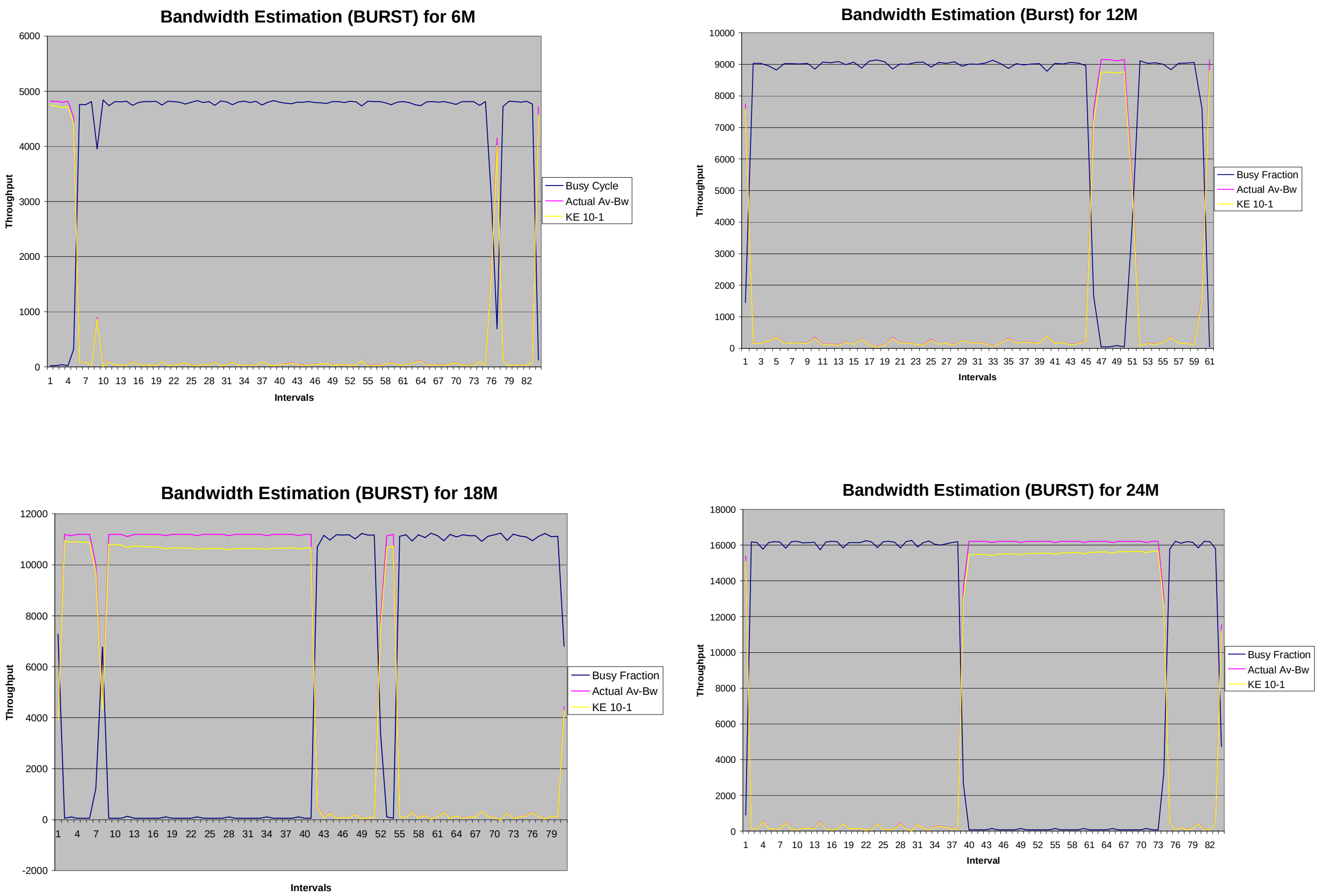


Figure 4: Av-Bw Estimation for Random Burst with varying rates to 6M, 12M, 18M and 24M.

Above experiments show that KF produced accurate estimation even with large variations in bandwidth. Especially in random burst, KF estimation with Q=0.1 has been efficient in predicting Av-Bw with uncertain variations in channel utilization. Note that in Random Burst, data could not be used for comparison due to randomized transmission.

5 KF vs. Abing & Pathload

Kalman Filter is compared with estimation produced by Active Measurement tools for Bandwidth Estimation. Active Measurement tools use packet probing and trains for bandwidth estimation. Two most used tools Abing and Pathload are compared for accuracy, measurement duration, consistency and network overhead.

5.1 Abing

Abing uses packet pair dispersion to estimate Av-Bw in network. It is based on estimating cross-traffic as a basic parameter. Probing packets are sent from Abing host with a known separation. Times between deliveries of adjacent packets in a pair are measured to calculate utilization of bottleneck link which is shown in figure 5.

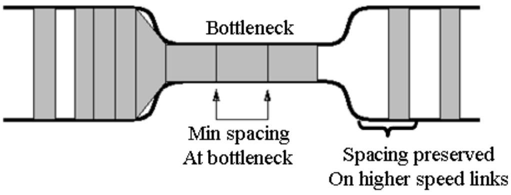


Figure 5: Abing bandwidth estimation.

Abing produces following series of numbers for each direction:

ABw: Estimated Available Bandwidth
Xtr: Estimated cross-traffic (instant value)
DBC: Dominated Bottleneck Capacity

Estimated Av-Bw is calculated using equation

$$ABw = DBC - Xtr \quad (5)$$

DBC is capacity of segment in the path (link) that at the measurement moment is causing a bottleneck. Usually router in this segment is overloaded and generates a burst of output packets that are tightly packed/closely spaced. DBC gives a measure of the capacity of segment where the cross traffic is highest at the moment of measurement.

Pathload

Pathload is developed based on the idea of SLoPS (Self-Loading Periodic Stream). Concept behind SloPs is; when process at Sender sends a periodic stream of UDP packet at data rate R higher than Av-Bw in the path, the relative one-way packet delays (OWD) show increasing trend. While, if stream rate is lower than Av-Bw, OWD show no consistent trend. Pathload sends “fleet of N streams" so that it has N samples to decide whether the rate R is greater than Av-Bw or not.

Figure 6: Pathload bandwidth estimation.

Figure 6 shows working of Pathload in detail. Pathload Sender sends approximately 100 probes of equal-sized packets at rate R and measure OWD. Rate R is modified with each iteration of the fleet. In figure 6, OWD increase only when rate R is larger than the Av-Bw A. Pathload tool reports a range (where OWD begins to incline) rather than a single estimate.

5.2 SCENARIO

To test the impact of interference on the performance of estimation tools, an experimental setup is established as shown in figure 7.

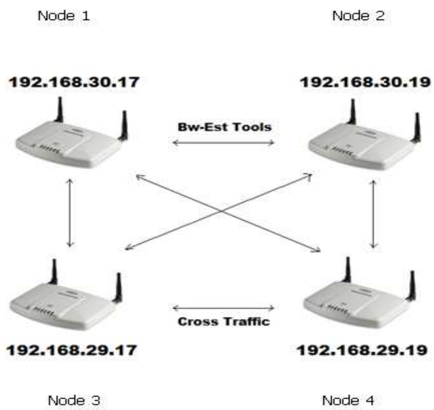


Figure 7: Experiment setup for testing Bw-Est tools

Two nodes 192.168.31.17 and 192.168.31.19 are chosen, each configured with two wireless interfaces ath0 and ath1. Interfaces ath0 and ath1 of 192.168.31.17 are configured as 192.168.30.17 and 192.168.29.17. Similarly interfaces ath0 and ath1 of 192.168.31.19 are configured as 192.168.30.19 and 192.168.29.19. In this experiment 192.168.30.17 and 192.168.30.19 are termed as node 1 and node 2 respectively, while 192.168.29.17 and 192.168.29.19 are kept as node 3 and node 4. Each of clients (node 2 and node 4) is associated with node 1 and node 3 respectively. All four nodes were in transmission range of each other.

Estimation tools were run between nodes 1 and 2, while nodes 3 and 4 were used to exchange cross-traffic (thus creating interference). Physical data rate of node 3 is kept as 6 Mbps. Cross-traffic was generated at a constant rate of 2.5 Mbps using a UDP traffic generator (200 p/sec, 1450 Bytes). Data rate of link running the estimation tools was varied from 6 to 24 Mbps (802.11a physical layer data rates).

Bandwidth estimations are calculated using KF, Abing and Pathload. Data is averaged for comparison as shown in Table 1. Actual Av-Bw is calculated from equation 2 using actual Channel Utilization (μ).

Table 1: Comparison between KF Estimate with Abing and Pathload.

Physical Rate	Actual Av-Bw	Average Kalman Estimate Q=0.1	Q=0.01	Q=0.001	Abing	Pathload Range From	Till
6	1979.19	1901.93	1916.61	1915	3450	2220	2290
12	3798.27	3651.96	3675.03	3676.28	10466.66	4290	5480
18	4746.96	4565.27	4588.02	4592.28	11750	3930	7380
24	6950.59	6680.95	6704.25	6720.4	15462.5	4650	8690

From above Table 1, it can be observed that KF estimates are producing the most accurate estimation. On the other hand, Abing has produced over-estimations. In case of Pathload, prediction range has been produced which is over-estimating the bandwidth with physical rate of 6M and 12M while producing accurate prediction range for 18M and 24M. This can be seen clearly in the graph shown in Figure 8.

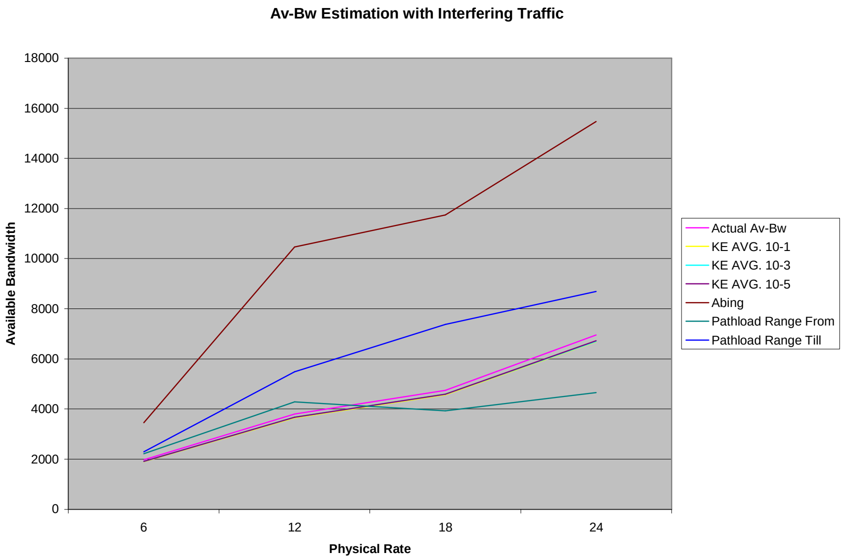


Figure 8: Bw-Est Tools Comparison.

Tools are tested for Periodic and Poisson data transmissions as shown in figure 9 and 10 in which Abing showed abnormal behaviour by producing high over-estimation.

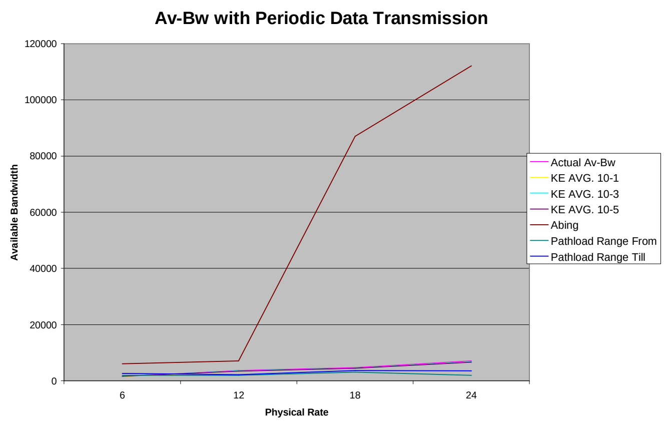


Figure 9: Bw-Est Tools Comparison for Periodic Traffic.

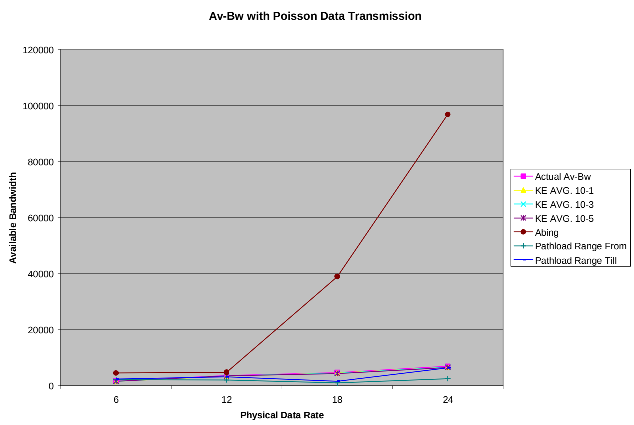


Figure 10: Bw-Est Tools Comparison for Poisson Traffic.

Why does Abing performed poorly?
To see in detail why Abing performed poorly for estimating bandwidth, several experiments were performed by altering physical rate of node 1 to 6M, 12M, 18M and 24M. A manual Periodic data transmission is produced as cross traffic between node 3 and 4. Abing is run at the peaks of maximum Av-Bw at certain iterations. The experiments are shown in figures 11 to 14. According to the graphs, Abing produced good results for physical rate 6M and 12M, while Abing performed very high over-estimations for rate 18M and 24M. Also it can be noticed that KF estimations for different values of Q performed accurate estimations comparatively to Abing estimations.

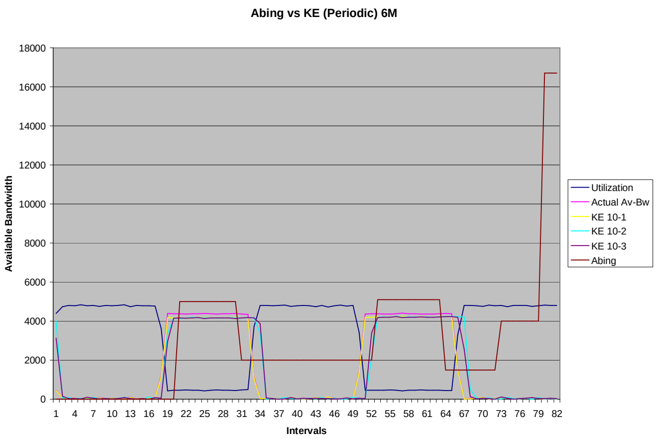


Figure 11: Abing Bw-Est at 6M.

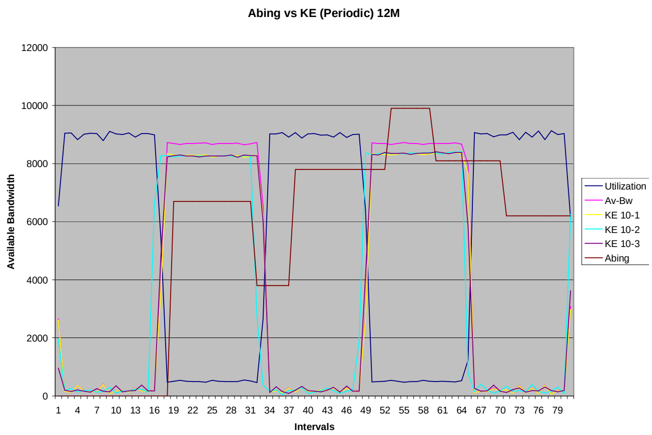


Figure 12: Abing Bw-Est at 12M.

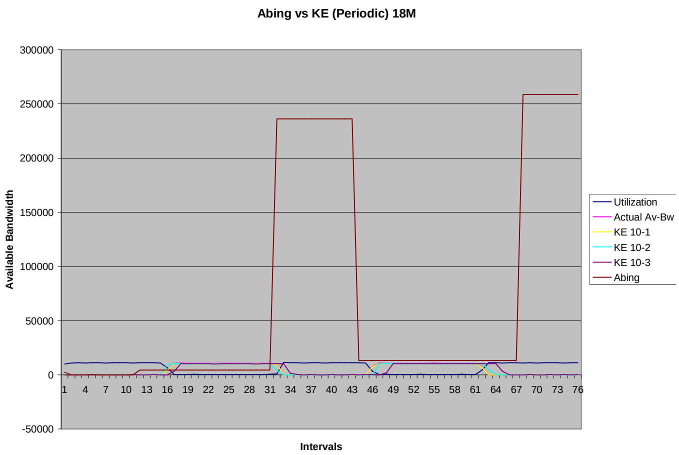


Figure 13: Abing Bw-Est at 18M.

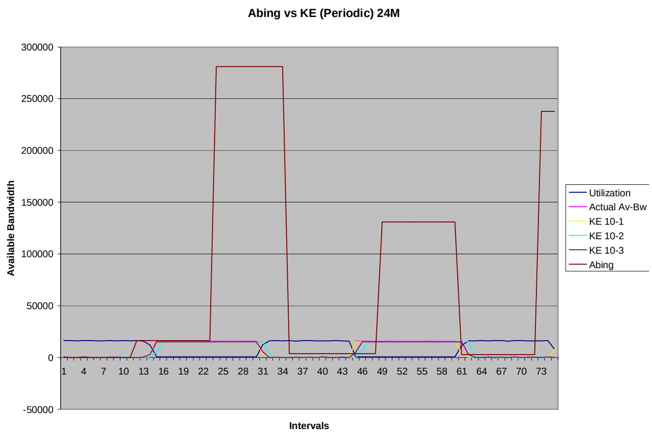


Figure 14: Abing Bw-Est at 24M.

According to Sriram and Murray [6], Abing sends 1500 byte packet pairs with some interval **t** between packet pairs. It computes Av-Bw by averaging the IAT (inter arrival time) between all the packet pairs. A normal IAT should be 11-13µs. Interrupt coalescence or delay quantization causes IAT jumps to 244µs in samples. These delays throw off high estimates.
Problems with Pathload
Two problems were found in Pathload estimations.

Problem 1: Under low load conditions, Pathload estimates the Av-Bw well irrespective of the cross-traffic packet size. Pathload overestimates Av-Bw when cross traffic is high. The reason is, with a contention-based MAC, if sender is sending at more than its fair share, and a second sender slowly starts ramping up its sending rate, then the first sender will be "pushed back" by MAC to its fair share, thereby giving the second flow its fair share as well. While this happens, output rate of probes matches their input rate, and there is no increasing trend in the OWDs of the probe packets. The net result is estimate tends to be the fair share rather than Av-Bw.

Problem 2: Cross-traffic on 6 Mbps channel appears as large bursts to Pathload probes sent on 18 and 24Mbps channels [5]. Pathload probes tend to queue up behind the large cross-traffic bursts. When channel becomes free, probes go out back-to-back. When Pathload's probing rate exceeds Av-Bw, typically there are only few large steps in OWD sequence, not the steady increasing trend that Pathload expects. End result is that Pathload is often unable to detect an increasing trend in OWD.

5.3 Analysis

Based on above experiments it is found out that:

- For higher modulation rates, it takes less time to transmit data traffic, and hence Av-Bw is higher.

- Pathload over-estimates the Av-Bw at high load. This is because 802.11 protocols try to provide MAC fairness to both the flows.
- Abing is over-estimating bandwidth by large amounts. This is because of per frame sharing of the channel, whereby only a small amount of cross-traffic (typically one frame) due to delay quantization, gets inserted between probe pair sent by Abing.
- KF estimations with Passive Monitoring returned the most accurate Av-Bw estimates.

Evaluation on the performance of Bw-Est tools has been made on the basis of accuracy of Av-Bw estimation, overhead, measurement duration and consistency of results.

Accuracy: In terms of Av-Bw estimation accuracy, Kalman Filter estimations are found most accurate for all physical rates. Pathload is accurate under low load that is when the physical rates are high. Also Abing showed problems at lower speeds in high physical rates.

Overhead: Kalman Filter has overhead of complex mathematical equations. This may cause short delays when used in passive monitoring. Pathload has 100 times network overhead of Abing.

Measurement duration: Kalman Filter is passive. The only delay is because of mathematical calculations**.** Abing is quick that is, it takes less than 1sec for measurement. Pathload takes tens of seconds. Measurement duration of Pathload depends on RTT which can timeout sometimes.

Consistency of results: Abing is very noisy and produces high variations in results. Pathload is smoother and multi-modal in producing results. Kalman Filter is consistent under low bandwidth variations and adapts to the changes quickly when the bandwidth variations are high.

6 Conclusion

Results from our experiments suggest that probe-based tools are not the best choice for wireless networks. Unique characteristics of wireless networks, such as a shared transmission medium, and use of rate-adaptation at link layer, cause these tools to provide inaccurate results. Delay quantization negatively affects tools using packet pair techniques like Abing. Using these tools over multiple wireless hops may cause further degradation in their performance. Kalman Filter passive scheme provided much more accurate results than the probe-based tools.

Future Work

This project could be extended by
- integrating Av-Bw estimation methodology with application by using data packets in place of probe packets
- Neural networks, ANFIS etc can be added for Av-Bw prediction.
- Different process models can be tested on each link. In case the process model varies with path, still KF can be used with some modifications to the system matrix.
- Impact of router buffer sizes on available bandwidth and achievable TCP throughput measurement can be analyzed.
- Other estimation tools & techniques like Netest, Pipechar, STAB, Pathneck, IGI/PTR etc can be compared.
- KF passive estimations may be developed for multi-hop networks.

7 Acknowledgement

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