Interference-Aware Decentralized Access Point Selection Policy for Multi-Rate IEEE 802.11 Wireless LANs

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***Abstract*—This paper proposes a new decentralized Access Point Selection Policy for 802.11 Wireless Local Area Networks (WLANs). We derive a decision metric towards AP selection improvement. The derived metric comprises both Inter-BSS and Intra-BSS interference. Our proposed policy is decentralized in the sense that the decision is performed by each station. The core of the policy is based on measurement reports standarized in the IEEE 802.11k standard. The main question we would like to address is: To what extent can the impact of interference be reduced at the selection phase ? The performance of the proposed policy is evaluated through detailed simulation experiments. We identify the scenarios where the proposed policy is likely to provide great gain, and scenarios where the gain is minimal.**

I. Introduction

It was not difficult for Wireless Local Area Networks (WLANs) to penetrate all homes, small offices, large companies and public hotspots. This has been fueled by three trends: The decreasing cost of wireless networking equipments like Access Points (APs) and WLAN cards; the fast advances in WLAN data rates; and the growing use of laptops and personal digital assistants (PDAs). Inline with the growth of WLANs, users' demands are also becoming more and their satisfaction becomes a challenging task for both network designers and administrators.

Before a station (STA) can join a Basic Service Set (BSS) and access data transmission services, it has first to discover the networks in its vicinity. This process is called scanning. The 802.11 defines two scanning modes, passive and active. In passive scanning, a STA simply hops over each channel on the supported channel list and listens for beacon frames transmitted periodically by APs. In active scanning mode, a STA itself tries to find the BSSs in its vicinity rather than waiting BSSs to announce themselves. A STA transmits a Probe Request frame on each channel on the channel list. APs respond to probe requests by sending Probe Response frames. After scanning, either passively or actively, a STA generates a scan report. The scan report includes all BSSs and their parameters collected during scanning. Then, a STA selects the BSS it wishes to associate with, matches its local parameters with the parameters received from the selected BSS and starts communication.

In current implementations of the 802.11 devices, AP selection decision is based on the Received Signal Strength Indication (RSSI). A STA simply selects the AP from which it has received the strongest signal during the scanning process.

This rather simple AP selection policy is not efficient and can even lead to problems regarding the network performance of larger areas with many STAs and several APs due to the following shortcomings:

- In addition to the connection quality, the quality of service (QoS) depends on many other parameters like the number of contending STAs and their individual loads, the amount of interference on the channel an AP offers. Therefore, the AP with which a STA has the highest RSSI does not necessarily provide the best service.
- RSSI based selection can cause load imbalance between several APs. In a dense Extended Service Set (ESS) with many APs, one could easily observe that many STAs associate with few APs while many other APs accommodate small number of STAs or even idle [1]. In this case, STAs do not efficiently utilize the available capacity. Consequently, with RSSI-based selection, radio resources are not effectively utilized and fairly shared among WLAN STAs.
- Practically, many STAs may have same connection quality with several candidate APs and probably employ same transmission rate to communicate with them. This is quite common with dense APs deployments of todays WLANs. The question still, how such STAs should select their APs?
- The multi-rate flexibility provided by several IEEE 802.11 variants can cause low bit rate STAs to negatively affect high bit rate ones and consequently degrade the overall network throughput. This problem is known as the Anomaly Problem and can be avoided at the selection phase.

Interference in WLANs is a core concern among both WLAN users and administrators. It degrades the performance of the WLAN due to errors and collisions. Generally, we can divide interference in infrastructure WLANs in two categories: Intra-BSS or intra-cell interference and Inter-BSS or inter-cell interference. The former is resulted from the simultaneous access of the wireless channel by STAs that belong to the same BSS. A STA wishes to send a data frame and was not able to detect or sense an ongoing transmission from another STA in the BSS will interfere/collide with the ongoing transmission. Both STAs are called hidden nodes and the problem is referred to as the hidden node problem. The later is resulted from simultaneous access of the wireless channel by hidden STAs that belong to different BSSs or cells that use the same channel and the transmission of one may reach the other's AP. Current WLANs rely on the MAC protocol to resolve Intra-BSS via the optional RTS/CTS mechanism while channel and transmission power selection algorithms have been proposed to alleviate the Inter-BSS interference.

In fact, the problem of AP selection has been tackled in many research activities. However, the focus has been given to the issue of balancing users' load among APs. The major question among the work in this area has been how to measure the load most realistically in a WLAN BSS. We give a brief overview of the art in section II. Motivated by our previous results of [2] and the Radio Resource Measurement Reports (RRM) the 802.11k standard [3] provides, this paper proposes a new decentralized policy for AP selection in 802.11 WLANs. We extend our prior model in [2] to account for both Intra-BSS and Inter-BSS interference. To characterize the inter-BSS interference, each BSS needs to know the active STAs that belong to neighboring BSSs and interfere the communication within its cell. This knowledge can be inferred via measurement reports of the 802.11k. The proposed policy is decentralized in the sense that the decision is performed at the STA side. The question we would like to address in this paper is: To what extend can the impact of interference be reduced through careful selection of the AP ?

The remainder of this paper is organized as follows: Section II discusses the state of the art. Section III describes the assumed system model. In Section IV, we propose our AP selection criteria. Section V discusses the implementation aspects of the proposed policy. Finally, we evaluate the performance of the proposed policy in Section VI before we conclude the paper in Section VII.

II. State of the Art

Currently, most of 802.11 WLAN adapters adopt the RSSI-based policy in order to select an AP to affiliate with. Previous works [4] [5] [6] have shown that the RSSI-based policy may lead to poor performance in terms of achieved throughput and load distribution. This has initiated intensive research studies that address this issue. A decentralized approach to load balancing has been proposed by Ekici et al. in [7]. Nevertheless, the authors suppose in their study that the achieved goodput per STA equals the transmission rate which is not the case in general. The authors of [8] compare the performance of selfish and centralized AP selection strategies. The paper of [9] proposes a scheme for best AP selection during handover based on frame retransmissions. While the proposed scheme achieves good performance, its implementation requires two wireless interfaces for each STA. The recent paper in [10] proposes to base AP selection on packet transmission delay. One concern about the proposed approach is the efficiency of estimating the set of required parameters during the scanning phase. In [11], the authors propose an AP selection policy that accounts for hidden node problem. With their approach, a STA selects the AP expected to provide the maximum throughput and minimum impact of STAs hidden from the new STA. Estimation of hidden STAs impact is based on channel busy time measurement during the scanning process and a channel busy time value provided by APs in beacon frames. A drawback of this approach is that a channel may sensed to be busy due to transmissions in other BSSs other than the one under consideration. Moreover, the throughput is simply concluded from the transmission rate estimated via RSSI. These issues may influence the accuracy of estimation. The work in [1] proposes an AP selection approach that considers the loss rate and the number of STAs already associated to an AP as a metric for AP selection. However, the authors ignore the interference aspect and the approach has been only tested for downlink traffic. The AP selection approach of [12] considers the interference in selection decisions. Nonetheless, the interference impact is derived from a curve generated experimentally for a specific topology and hence does not apply to all scenarios. Recently, the authors of [13] propose an AP selection policy based on the instantaneous rate and the fraction of time for which an AP acquires the channel for its transmission. While the derived model involves interference, it considers only downlink and assumes that channel contention is among APs. In our paper of [2], we have considered the mixed rate scenario and proposed a decentralized AP selection policy that bases AP selection on the STA's effective throughput and its impact on other STAs throughput, which are already associated to an AP of a BSS. The effective throughput is computed based on an estimation of the average time required to transmit a frame successfully over the wireless channel. Through simulation examinations, we have shown that the policy performs better than the legacy selection policy currently implemented in IEEE802.11 devices. Nonetheless interference from other nodes has been ignored.

A. Key Contribution

The AP selection policy we propose in this paper copes with both Inter-BSS and Intra-BSS interference. We derive a new metric for AP selection that incorporates errors due to packets collisions and losses. Inline with the ongoing discussions within the standarization bodes which advocate measurement based approaches, our policy is driven by parameters deduced from on-line measurements transported via

802.11k mechanisms. We exploit the possibility of improving performance experienced by users by reducing the interference at the selection phase.

III. System Model

We consider a standard ESS 802.11 WLAN. The WLAN is comprised of ***N*** BSSs and ***M*** users (STAs). All APs are connected to a single distribution system (DS) which connects them to the wired network. Due to the lack of non-interfered channels that the 802.11 standard supports, some APs are assigned the same channel. APs provide communication services to the ***M*** users that reside within their coverage area. At any time instant, a user is associated to a single AP. We denote the set of STAs associated with AP i as S_i. At the MAC layer, APs and users employ the DCF mode with CSMA/CA channel access protocol. A transmitting node dynamically adapts its transmission rate. The signal attenuation is mainly affected by path loss and fading. The coverage areas of APs are assumed to overlap. Further, we assume that both STAs and APs are 802.11k-enabled.

The 802.11k standard [3] defines a set of measurement reports to be exchanged among STAs and their APs to facilitate efficient radio resource management strategies. The standarized reports provide knowledge about the WLAN status such as: neighbor information, channel load, hidden nodes statistics, etc. The way in which the reports could be used for radio resource management has not been specified. In our work, we utilize the (**Beacon Report**). When it receives a **Beacon Request** from its AP, a measuring STA monitors the RF environment and responds with a summarized information (the 802.11k **Beacon Report**) about the detected beacons from neighboring BSSs. We elaborate more on this point in section V.

IV. A new metric for AP Selection

In our prior work published in [2], we proposed a decentralized AP selection scheme whereby a STA selects the AP that provides the maximum throughput while at the same time evaluating the potential impact of the association on already associated STAs in the same BSS. Therefore, a STA tries to minimize its negative effect on other STAs if its theoretical throughput from the candidate APs does not differ significantly. This reduces the so called Anomaly Problem in 802.11 WLANs at the selection phase. However, the model of [2] does not take into account the potential packet error due to intra-BSS and inter-BSS interference.

For the sake of clarity, we first re-write the main equations and define the involved parameters. More details can be found in [2]. A STA k selects an AP that maximizes the following cost function:

$$W(i) = \alpha \frac{L}{\overline{T_{k,i}} + \sum_{j=1}^{U_i} \overline{T_{j,i}}} + (1-\alpha)\frac{\sum_{j=1}^{U_i} \overline{T_{j,i}} - U_i \overline{T_{k,i}}}{U_i(U_i+1)} \quad (1)$$

where:

$$\overline{T_{k,i}} = T_{k,i}(0) + \sum_{j=1}^{\infty}(1-P_{k,i})P_{k,i}^{j}\left[\sum_{m=0}^{j-1} T_f(m) + T_{k,i}(j)\right] \quad (2)$$

$$T_{k,i}(j) = T_P + T_H + T_{\mathrm{DIFS}} + \frac{L}{R_k} + T_{\mathrm{SIFS}} + T_{\mathrm{ack}} + T_{\mathrm{backoff}}(j) \quad (3)$$

$$T_f(m) = T_{\mathrm{P}} + T_{\mathrm{H}} + T_{\mathrm{DIFS}} + T_{\mathrm{backoff}}(m) + \frac{L}{R_k} + T_{\mathrm{SIFS}} + T_{\mathrm{ack}} + T_{\mathrm{Slot}} \quad (4)$$

$$T_{\mathrm{backoff}}(j) = \begin{cases} \frac{2^j(W_{\min}+1)-1}{2} \cdot T_{\mathrm{Slot}} & 0 \le j < 6 \\ \frac{W_{\max}}{2} \cdot T_{\mathrm{Slot}} & \mathrm{j} \ge 6 \end{cases} \quad (5)$$

The first term of 1 corresponds to the throughput that STA k is expected to experience if it selects AP i. The second term is a measure for the impact of STA k on other STAs accommodated by AP i. α: is a weighting factor between 0 and 1. U_i: is the number of STAs in BSS i. $\overline{T_{k,i}}$: is the average time span that STA k requires to transmit a single frame correctly in BSS i. $P_{k,i}$: is the frame error probability. $T_f(m)$: is the time between two consecutive transmissions if the frame transmission fails. $T_{k,i}(j)$: is the raw average transmission time of a frame. T_{P} and T_{H} represent the time duration of the physical layer preamble and header respectively. T_{DIFS}: is the Distributed Coordination Function Inter-frame Space and T_{SIFS} is the Short Inter Frame Spacing. $L = (28 + L_{\mathrm{MSDU}}) \cdot 8$: is the length of the MAC packet in bits. T_{ack}: is the duration of the ACK frame. $T_{\mathrm{backoff}}(j)$ is the average backoff interval in μs after j consecutive unsuccessful transmission attempts. T_{Slot}: is the basic slot duration. $W_{\min}$ and $W_{\max}$ are the minimum and maximum contention window sizes respectively.

That was mainly the prior model of [2]. Now we extend the model and incorporate the interference aspect which becomes essential specially in dense WLAN deployments due to the limited number of supported channels by 802.11 standards. Let us focus on frame error probability $P_{k,i}$. In fact a transmission can fail due to losses or collisions. Assuming that losses are independent from collisions, we can write $P_{k,i}$ as follows:

$$P_{k,i} = e_{k,i} + c_{k,i} - e_{k,i}c_{k,i} \quad (6)$$

where $e_{k,i}$ is the loss probability due to the channel and $c_{k,i}$ is the error probability due to collisions. In [14], Bianchi et al. derived an expression for the $c_{k,i}$ assuming that any simultaneous transmissions collide as follows:

$$c_{k,i} = 1 - (1-\tau_k)^{U_i - 1} \quad (7)$$

where τ_k represents the probability that STA k transmits in a randomly chosen time slot expressed as:

$$\tau_k = \frac{2(1-2c_{k,i})}{2(1-2c_{k,i})(W_{min}+1) + c_{k,i}W_{min}(1-(2c_{k,i})^m)} \quad (8)$$

where $m = Log_2(W_{max}/W_{min})$, (i.e when W_{min}=32 and W_{max}=1024, then m=5).

To incorporate the influence of inter-BSS interference (i.e interference due to transmissions in neighboring BSSs), we modify (7) as follows (taking into account the new STA S_k):

$$c_{k,i} = 1 - (1 - \tau_k)^{U_i} \prod_{\forall j, j \notin S_i} \Theta_{j,k} \quad (9)$$

where $\Theta_{j,i}$ is the probability that STA j does not collide with the transmission of STA k which can be expressed as:

$$\Theta_{j,k} = (1 - \tau_j) + \tau_j(1 - \xi_{k,j}) \quad (10)$$

where $\xi_{k,j}$ is the probability that a transmission from STA j in a neighboring BSS disrupts a simultaneous transmission of STA k. In fact the value of $\xi_{k,j}$ depends on channel conditions and specifically the level of the received signal from STA j at AP i, the AP of STA k. The first term on the right side of (10) represents the probability that STA j does not transmit while the second term represents the probability that STA j transmits but does not disrupt STA's k transmission. Assuming $\tau_j = \tau, \forall j$ and substituting (10) in (9), we have:

$$c_{k,i} = 1 - (1 - \tau)^{U_i} \prod_{\forall j, j \notin S_i} (1 - \tau\xi_{k,j}) \quad (11)$$

V. AP Selection Policy and Implementation Aspects

In this section we elaborate the proposed selection policy and discuss the challenging issues toward its implementation. Basically, a STA selects the AP which maximizes the cost function $W(i)$ of (1) (i.e. maximizes its theoretical throughput while minimizes its impact on others). In order to compute the cost function, a STA needs to acquire the following pieces of information from its potential AP: The summation value in (1), the number of active users that an AP accommodates U_i and the number of interfering STAs from neighboring cells N_j. The computation of the summation is described in [2]. While an AP already knows U_i, it can infer N_j from two sources: **(i)** The local measurements at the AP: Each AP can monitor its operational channel and observe the activity of unassociated STAs in its vicinity. The main drawback of this option is the difficulty for the AP to perform measurements when the downlink traffic is high (i.e. AP can not monitor and transmit simultaneously). **(ii)** Utilizing the 802.11k **Beacon Report**: APs send Beacon requests to associated STAs, asking these to report beacons they receive from other BSSs that use the same channel. A STA that agrees to conduct measurements observes all beacons transmitted by other APs in its vicinity. At the end of the measurement time, a STA processes measurements and send the beacon report to its AP. Any STA that can not perform the measurement at any time point may report the results of the most recent measurement. Since the CSMA provides per frame fairness, each STA will have the chance to use the channel. Therefore, it is possible for each AP to estimate the activity of all STAs it accommodates by observing the in/out frames during some time interval. Consequently, each AP has the knowledge of: *Which of its associated STAs interfere other neighboring BSSs*. To avoid excessive overhead, APs increment the time between two consecutive beacon requests if the most recent beacon report does not differ from its precedence. Practically, an AP either transmits a beacon every 10 or 100ms depending on the configuration. In order to assure that transmitted beacons from neighboring AP fall in the observation period, this period has to be at least 100ms. If APs share measurement results, each one can deduce the number of interfering STAs N_j in its neighborhood and belong to other BSSs. APs include U_i and N_j in beacons and probe response frames. Thus, the error probability due to collisions (equation (11)) may be written as:

$$c_{k,i} = 1 - (1 - \tau)^{U_i + N_j} \quad (12)$$

where N_j is the number of potential interferers to STA k if it associates to AP i. The AP could include the required values in a new information field in beacons and probe response frames. Obviously, the length of this field is only a few bytes, so that it does not impose significant overhead. As proposed in [14], $c_{k,i}$ can be found by solving (12) and (8) numerically, $e_{k,i}$ can be estimated from the received signal power. Having these values, a STA computes $P_{k,i}$, $\overline{T_{k,i}}$ and the cost function $W(i)$ respectively.

VI. Performance Evaluation

In this section we evaluate the performance of the proposed AP Selection policy. We have conducted extensive simulation experiments using the NCTUns simulation package [15]. The MAC protocol of NCTUns is ported from NS-2 network simulator which indeed implements the complete IEEE 802.11 standard MAC protocol to accurately model the contention of users for the wireless channel. As evaluation metric, per second throughput at the link layer is used. In the following, we first discuss the simulation model, afterwords we discuss our results.

A. Simulation Scenario

The simulation scenario comprises 10 BSSs deployed in a 500m X 500m area. The three non-overlapping channels (1,6 and 11) are assigned to the 10 APs based on the legacy optimal channel assignment approach (i.e adjacent APs are assigned different channels). An AP counts an unassociated STA as inter-BSS interferer if it is able to receive its packets. All WLAN nodes implement the 802.11b technology and operate with DCF modus. The traffic was generated with the **stg** tools that come with the NCTUns simulation package. To consider a more realistic conditions, the communication range is set by the NCTUns based on the physical transmission rate and transmit power. A sender selects the physical transmission rate based on the distance d to the receiver. Table I lists the values of the parameters as used in simulations. A Rayleigh fading model provided by the NCTUns simulator was used. For the path loss we have used a two ray ground reflection

Parameter	Value	Parameter	Value
PLCP header T_H	48 μs	T_{SIFS}	10 μs
PLCP preamble T_P	144 μs	T_{DIFS}	50 μs
Cell overlap	20 %	T_{Slot}	20 μs
Fading Variance	10 dB	$W_{\min}$	31
APs/STAs Tx Power	100 mW	$W_{\max}$	1023
h_{tx} and h_{rx}	1 m	G_{tx} , G_{rx}	0 dBi
d $\leq$ 40	11Mbps	40 < d $\leq$ 80	5.5Mbps
80 < d $\leq$ 120	2Mbps	d > 120	1Mbps

TABLE I
CONSTANT PARAMETERS

model.

We evaluate the performance of our proposed policy in two scenarios. In the **First Scenario**: all users were randomly distributed across the coverage area of the 10 APs. In the **Second Scenario**: we consider an area like a conference hall or a waiting hall in an airport equipped with 5 APs. Most of the users were distributed in hall area. The other 5 APs are deployed in the neighborhood with less users density. Each scenario has been simulated for 30 different network topologies.

B. Simulation Results

In this section we present the results of our simulation experiments for the two scenarios described in section VI-A. We compare our results with the recent results of Fukuda et al. [1] and Kauffmann et al. [13].

*1) **First Scenario**:* Figure 1 compares throughput performance of the RSSI-based, Fukuda's [1] and our proposed AP selection policies under different uplink CBR UDP traffic loads when the network hosts 50 users. Figure 2 shows the throughput achieved with the three policies as a function of the number of users. We have the following observations: **(i)** In general our approach outperforms the other two approaches especially with heavy load as it considers the possible collisions due to interference. **(ii)** Under low load the performance of the three polices is almost the same. This is due to the fact that the MAC will have some time to retransmit a lost packet before the next comes from upper layers. In fact this observation advocates the necessity of considering how active a user is ? **(iii)** As our policy guides a user to avoid an AP that is reached by other interfering users, the achieved gain improves as the number of users increases (29% with 70 users).

*2) **Second Scenario**:* Figure 3 shows the throughput performance of the proposed policy in the second scenario. Since Fukuda's algorithm considers the number of users in the decision metric, it also pushes many users to the far APs and consequently achieve good gain. However, the results show that more gain can be achieved if the losses due collisions is taken into account as with our policy.

*3) **Downlink Traffic**:* We finally compare our policy with the RSSI-based, Fukuda's [1] and Kauffmann's [13] policies with saturated downlink TCP traffic and 50 users. Simulation results are shown in figure figure 4. Because there is little interference from users (only ACKs) in this scenario, we observed that our policy is just 6% better than the policy of Kauffmann [13] and 21% better than the RSSI-based approach.

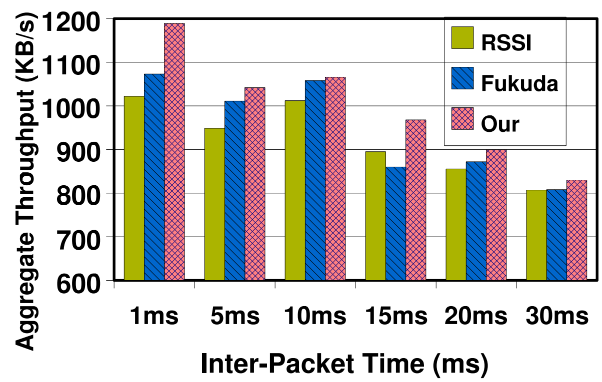

Fig. 1. First Scenario: Throughput Performance of uplink CBR traffic from 50 users with different packet inter-arrival time and different selection policies

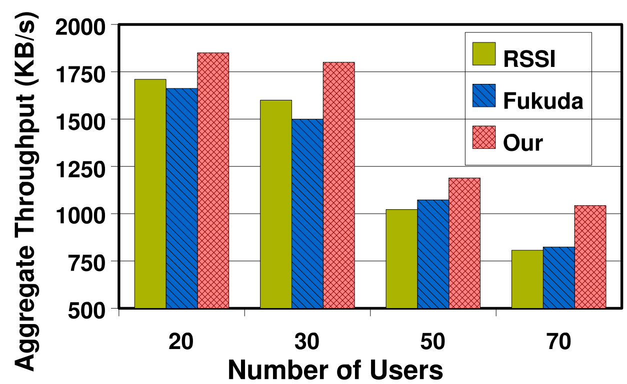

Fig. 2. First Scenario: Throughput Performance of uplink CBR traffic with 1ms inter-packet time for different number of users and different selection policies

VII. CONCLUSIONS

The legacy AP selection policy implemented currently in IEEE 802.11 WLANs adapters does not effectively utilize WLAN resources as it ignores important parameters that determines the QoS. In this paper we propose an improved AP selection policy for 802.11 WLANs that takes care of both Intra-BSS and Inter-BSS interference. The proposed metric encapsulates several cell and connection parameters into a

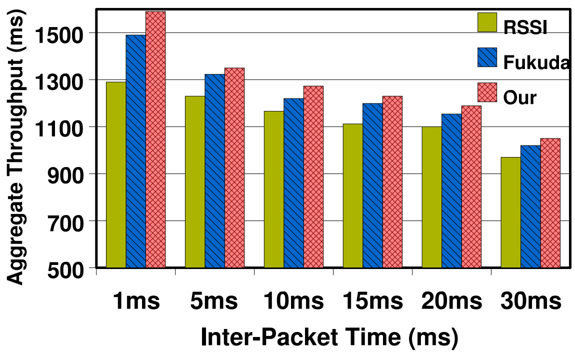

Fig. 3. Second Scenario: Throughput Performance of uplink CBR traffic from 50 users for different packet inter-arrival time and different selection policies

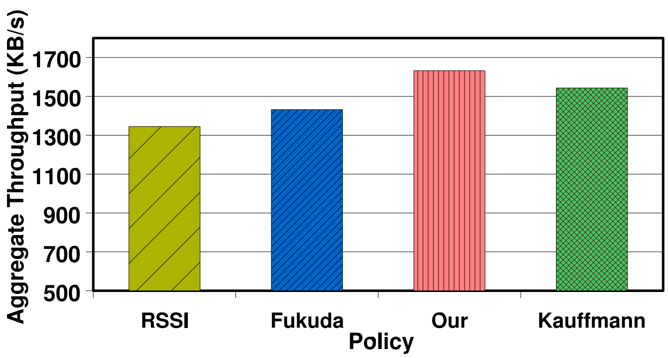

Fig. 4. First Scenario: Performance comparison of AP Selection policies with saturated downlink TCP traffic for 50 users

single value. Simulation results show that a measurement-driven policy can reduce the interference impact and enhance users QoS by improving aggregate network throughput especially under high load and uneven STAs distribution across the coverage area.

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