Handover Incentives: Revised Model with Extensions for Uplink Traffic

Xenofon Fafoutis[1] and Vasilios A. Siris[1, 2]

[1]Institute of Computer Science, Foundation for Research and Technology – Hellas
Heraklion, Greece, email: {fontas,vsiris}@ics.forth.gr

[2]Athens University of Economics and Business, Athens, Greece

Abstract

Focusing in competitive environments where each party acts in its own self-interest and not towards a common goal, the objective of this paper is to investigate the incentives that can trigger handovers of wireless nodes that operate at low rates to neighboring access points that operate in the same channel but belong to other networks. The handovers address the well-known problem in IEEE 802.11 networks, that the assignment of low-rate and high-rate users to the same access point significantly degrades the performance of the high-rate users. This fact gives rise to incentives for performing handovers, due solely to the improved performance handovers yield for both wireless networks. In order to investigate when such incentives arise for wireless networks operating in the same contention area, and to quantify the corresponding gains, a modeling framework is proposed. The modeling framework estimates the throughput of wireless nodes in IEEE 802.11 WLANs and aims to identify the specific cases that handovers yield performance improvements and advise the wireless network operators whether or not to share their resources. This paper extends our previous work (Fafoutis & Siris 2009) by integrating a revised analytical model which includes the case of uplink traffic and provides more accurate approximations. The analysis indicates that there can be significant performance improvements for both parties in both the case of downlink and uplink traffic. The accuracy of the modeling framework is verified through simulations.

Keywords

Handovers, Cooperation Incentives, IEEE 802.11

1. Introduction

The objective of our work is to investigate the incentives for handovers between self-interested IEEE 802.11 networks with overlapping coverage. Handovers of wireless nodes that operate at low rates to neighboring access points that belong to other networks can improve the performance of both parties. Through such cooperation, the throughput degradation due to the well-known performance anomaly (Heusse et al. 2003) is avoided. Of course, such cooperation between operators can also result from agreements that involve monetary exchange or interconnection agreements similar to those that exist between telephony operators. However, the focus of our work is on the cooperation incentives due *solely* to the improved performance that cooperation yields for *both* wireless networks. The main assumption of these scenarios is that two or more access points operate in the same channel. Indeed, it is common that there are more than three access points within the range of each other (Akella et al. 2007). Hence, the three orthogonal channels available in 802.11b/g are not sufficient to assign orthogonal channels to different access points. Moreover, available

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This work is supported in part by the European Commission in FP7 through project EU-MESH, ICT-215320.

non-overlapping channels will be further reduced as more wireless networks operating in unlicensed bands are deployed over time and as channel combining techniques are used to increase transmission speeds.

In order to investigate when such incentives arise for wireless networks operating in the same contention area and to quantify the corresponding gains, we propose a modeling framework, which estimates the throughput of wireless nodes in 802.11 WLANs. A key feature of the model is that it captures the effects of rate diversity on the throughput. The model aims to identify the specific cases that cooperation yields performance improvements and consult the wireless network operators whether or not to proceed to the handovers.

The main contribution of our study lies in the incentives that arise by the fact that handovers between self-interested operators can yield significant performance improvements. The key difference to prior work is the focus on competitive parties that act at their own self-interest and there is no other cooperation between them, such as monetary exchange or other forms of enforcement. Prior work, on one hand, aims to improve the performance of single networks or cooperative networks that work towards a common goal. Related work in competitive environments focuses on ways to enforce cooperation. Our focus, on the other hand, is to identify when cooperation can be motivated solely by performance improvements; hence, without requiring any enforcement or other form of cooperation. Related work is further discussed in Section 5.

This paper extends our previous study on handovers incentives between WLANs (Fafoutis & Siris 2009) with the following additional contributions. In addition to the downlink direction, in this paper we model and investigate the uplink direction. Additionally, this paper discusses the implementation details of the proposed procedure. Lastly, the paper includes a revised easily-extendable version of the analytical framework which includes the application of an improved protocol overhead model. We stress that the evaluation suggests that the revised model provides even more accurate throughput approximations.

The rest of the paper is organized as follows. Section 2 describes and the throughput model and a series of analytical investigations. Section 3 evaluates the model through comparison to simulation results. Section 4 discusses the implementation details. Finally, Section 5 discusses the related work and Section 6 concludes the paper.

2. Throughput Model and Analysis

Consider the case of two access points, AP_0 and AP_1, Figure 1 (left). AP_0 sends traffic to N_0 nodes at high rate R and to N_0^x nodes at low rate r. These are the clients of AP_0 and its actions target to improve their throughput. AP_1 sends traffic to nodes N_1 at high rate R. Nodes N_0^x are closer to AP_1 and would transmit at a higher rate R, if they were associated to it. This is the scenario, which we will refer to as *case a*. The following assumptions are made: (a) both access points operate at the same channel, (b) all access points and nodes are in the same contention area and (c) there is at least one node in each of the three node sets. The objective is to identify when both parties have performance-oriented incentives that can trigger the handovers of the low rate clients (N_0^x) of AP_0, to the neighboring access point AP_1. This is the scenario shown in Figure 1 (right), which we will refer to as *case b*. Now, AP_1 sends traffic only to the N_0 nodes at high rate R, while AP_1 sends traffic at high rate R to both its own clients (N_1) and the ex-low-rate clients of AP_0 (N_0^x). The analysis that follows focuses on the above topology, which encompasses the key tradeoffs we want to highlight.

The throughput gain of AP_i is defined as the ratio of the aggregate throughput of the clients of AP_i in *case b* (N_0^x clients associated to AP_1), over *case a* N_0^x clients associated to AP_0). When the gain for both access points is greater than 1, handover improves the throughput of the clients of both access points. Additionally, the throughput model considers the function $T(p, R)$, which denotes the expected duration for the transmission of a frame with payload size p, when the transmission rate is R. If we disregard all overheads, this function is given by $T(p, R) = p/R$. This expression captures a key property of wireless networks, namely that the duration of a frame transmission is higher for nodes with a smaller transmission rate.

Figure 1: Case a: No Handovers (left), case b: Handovers (right).

2.1 Model for the Downlink Direction

Next we present a model for the throughput in saturated conditions for the downlink direction. Since the DCF protocol of 802.11 provides long term fair channel access, the APs will send an equal amount of frames over a long time interval. Hence, it is equivalent to a round-robin system where each transmitter sends one frame in each round.

When N_0^x nodes are assigned to AP_0, the expected time that AP_0 needs to transmit a frame depends on its destination, since the duration of the transmission is different due to the different rates. On the other hand, the expected time interval that AP_1 needs to transmit a frame is independent of the number of its nodes since all operate at the same rate. The long term throughput that each access point will achieve, namely X^a, assuming both access points transmit frames of the same size, is given by

$$X^a = \frac{p}{\frac{N_0}{N_0 + N_0^x} T(p, R) + \frac{N_0^x}{N_0 + N_0^x} T(p, r) + T(p, R)} \quad (1)$$

where N_0 and N_0^x are the number of nodes in the N_0 and N_0^x node-set respectively. In the case that the low rate nodes are handed over, the long term throughput that each access point will achieve, namely X^b, is equal to

$$\mathrm{X^b} = \frac{\mathrm{p}}{2\ \mathrm{T(p, R)}} \quad (2)$$

The throughput of each client can be calculated by equally sharing the throughput of each access point to the number of the clients it served. Then, the gain of each access point is calculated by assigning the respective estimated throughput to the ratio previously defined. The key tradeoff is the following. When low-rate nodes are associated to AP_0 (*case a*), throughput is reduced. On the other hand, when the low-rate nodes are associated with AP_1 (*case b*), AP_1 shares its share of the wireless channel with the N_0^x nodes, which are AP_0's clients. It is obvious that *case b* is always beneficial for AP_0, since AP_0's clients not only utilize the wireless channel for more than half of the time, but the throughput also improves due to removing low-rate transmissions. The following inequalities

$$Gain_{AP_0} = \frac{X^b + \frac{N_0^x}{N_0^x + N_1} X^b}{X^a} > 1 \quad \text{and} \quad Gain_{AP_1} = \frac{\frac{N_1}{N_0^x + N_1} X^b}{X^a} > 1 \tag{3}$$

are necessary conditions for handover to be beneficial for both access points. Since $X^b > X^a$, the $Gain_{AP_0} > 1$ is always satisfied. However, if the assumption $N_0 > 0$ does not hold, then *case b* is not always beneficial for AP_0. This inequality can be used by AP_1 to decide if it is beneficial to serve the low-rate nodes of his neighboring access point AP_0.

2.2 Model for the Uplink Direction

Next, we investigate the uplink direction. In the case where the traffic originates from the wireless clients and is headed to the access points, each node contends for the wireless medium. Assuming each client transmits one frame in each round, for *case a* and *case b* the throughput of each node is:

$$X_{N_0}^a = X_{N_0^x}^a = X_{N_1}^a = \frac{p}{N_0\, T(p,R) + N_0^x\, T(p,r) + N_1\, T(p,R)} \tag{4}$$

$$X_{N_0}^b = X_{N_0^x}^b = X_{N_1}^b = \frac{p}{N_0\, T(p,R) + N_0^x\, T(p,R) + N_1\, T(p,R)} \tag{5}$$

The following inequalities

$$Gain_{AP_0} = \frac{N_0\, X_{N_0}^b + N_0^x\, X_{N_0^x}^b}{N_0\, X_{N_0}^a + N_0^x\, X_{N_0^x}^a} > 1 \quad \text{and} \quad Gain_{AP_1} = \frac{N_1\, X_{N_1}^b}{N_1\, X_{N_1}^a} > 1 \tag{6}$$

are necessary conditions for handover to be beneficial for both access points. Obviously, as long as $R > r$, the gain inequalities $Gain_{AP_0} > 1$ and $Gain_{AP_1} > 1$ are always satisfied, indicating that the handover is always beneficial for both access points.

2.3 Analytical Investigations

In this section we present a series of analytical investigation that aim to identify the gains of handovers. The protocol overhead is important to precisely estimate the throughput. For the analytical and simulation experiments that follow we consider an improved overhead model based on the theoretical maximum throughput (Jun et al. 2003). This overhead model is described in detail in our previous work (Fafoutis & Siris 2010). Additionally, we assume that the number of the nodes of each access point follows a normal distribution with a mean equal to 6 and a variance equal to 2. Experiments, omitted due to space limitations, suggest that the trends of the handover incentives do not depend on the distribution parameters. In order to evaluate the long-term gain we use the following metric:

$$NormGain_{AP_i} = \frac{1}{N} \sum_{k=1}^{N} x_{i_k} \; where \; x_i \begin{cases} Gain_{AP_i} & : handovers \\ 1 : & no\ handovers \end{cases} \tag{7}$$

When the model predicts that $Gain_{AP_i} > 1$ for all access points then the handovers are performed and each AP has a throughput gain. The normalized gain is an average of beneficial scenarios where the model suggests handovers and scenarios where no handover is performed. Therefore, this metric can capture both the frequency and the gains of a beneficial scenario. Additionally, this metric captures the effects of potential false positives and negatives. The following investigations are over 2000 samples.

Figure 2 (left) depicts the normalized gain for the downlink direction in *802.11b* and *802.11a* for various values of the low rate r. The rate R is equal to the highest rate supported by each protocol, 11 Mbps and 54 Mbps respectively. We have observed similar behavior in both protocols. The small differences are due to differences in their overhead. Observe that there are significant long-term performance improvements when the rate r is low; less or equal to 2 Mbps and 12 Mbps in *802.11b* and *802.11a* respectively. For higher rates, r, the beneficial scenarios are a few. However, the normalized gain is always positive, as the model can predict when the handovers are beneficial. Figure 2 (right) shows the normalized gain for the uplink direction in *802.11b* and *802.11a* for various values of the low rate r. In this case, the normalized gain is equal for both access points. This occurs because in the uplink direction all clients contend for the channel and the bandwidth is fairly shared between them. Additionally, we note that for higher values of r, the normalized gain in the uplink direction is significantly increased compared to the downlink direction. For low values of r, the normalized gain resembles the normalized gain of AP_0 in the downlink direction.

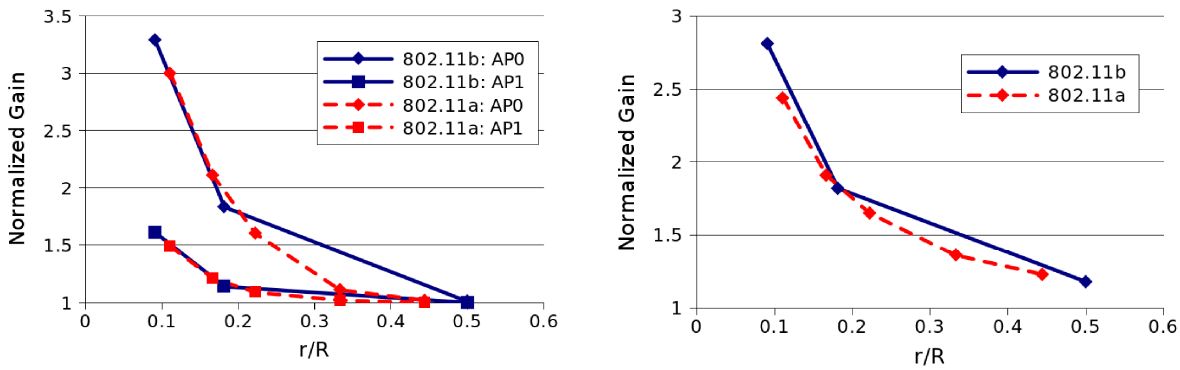

Figure 2: Traffic in the downlink (left) and the uplink (right) direction.

3. Evaluation

The accuracy of the revised analytical model is evaluated through simulations on NS-2, and is verified that it can accurately estimate the throughput gains that are achieved through handovers. We extended NS-2 to support multiple rates for transmissions between one transmitter and multiple receivers. We simulate the *802.11b* version of the base scenario. The low rate, r, is 1 Mbps and the high rate, R is set to the maximum available rate supported by the protocol, namely 11 Mbps. The presented results show the normalized gain over all the potential scenarios, assuming that each AP serves up to 10 nodes. The experiments used UDP traffic, and each run had duration 15 seconds. The column named *Analytical Model* in Figure 3 (left) refers to the analytical approximations as estimated by the proposed model.

The simulations indicate if the model is used for accepting or rejecting handovers, there are 0.4% false positives and 2% false negatives. The column *NS-2 Optimal Filter* refers to a theoretical optimum filter that perfectly predicts the beneficial and non-beneficial scenarios. The figure shows that the handover policy, which based on the model (in figure named *NS-2*), performs extremely well, giving a normalized gain for AP_1 which is within 0.01% of the maximum gain, which is achieved by the theoretical optimal filter. The normalized gain for AP_0 is within 4% of the theoretical maximum gain. This happens because false predictions occur on scenarios with marginal gains or losses. As a result, they have insignificant effects on the normalized gain. The accuracy of the model is also verified as its estimations are very close to the results of the simulation experiments.

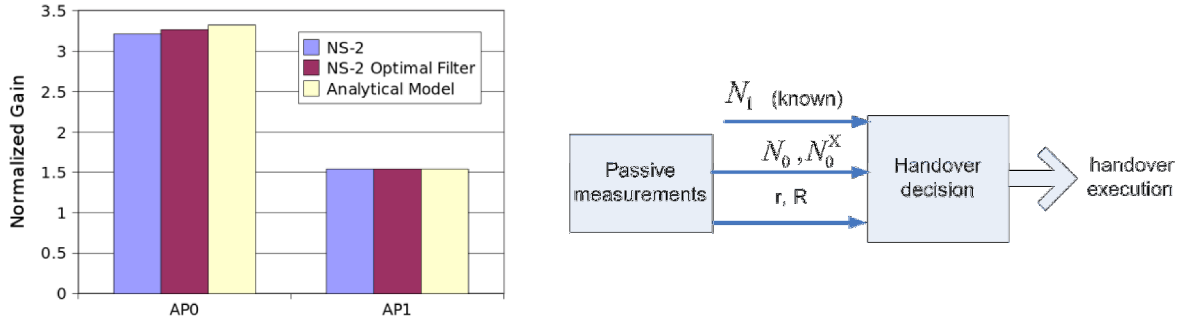

Figure 3: Model evaluation through simulations (left) and the handover process (right)

4. Discussion on Implementation

The handover process followed by AP_1 is being depicted in Figure 3 (right). As it is shown there, the AP_1 is performing passive measurements for nearby stations to examine the existence of low rate transmissions and then it can extract from the measurements the needed information to compute (3) to take a decision if it will request the handover of the low rate nodes. If (3) is satisfied, then AP_1 will continue to the execution of the handover and communicate with AP_0 for the rest of the handover process. The handover acceptance policy requires that the access points know the number of connected nodes and their rates. Assuming that there are no hidden nodes, this information is easy to obtain by monitoring the neighboring traffic. The access point can count unique MAC addresses and extract the rates from their PLCP header. Alternatively, the neighboring access points can directly communicate and exchange all the information required. This approach provides a solution in the case of hidden nodes. However, issues arise if malicious access points may provide false information. Additionally, the access point needs to estimate the rate that the low rate nodes would operate at, if handovers are performed. Measuring the received signal strength of the frames the low rate nodes transmit can be useful for this estimation. Upon recognition of a beneficial scenario, there are two approaches for the handovers themselves. First, the access points can directly communicate, exchange the required information and execute the handovers. Alternatively, AP_0 does not need participate. Whenever AP_1 recognizes that it can serve neighboring nodes at higher rates with gains for its clients, it can allow the low rate nodes to associate with it.

5. Related Work

In this section we briefly summarize related work. Zdarsky et al. (2006) argue that operators would benefit if their APs were enabled to cooperate and form a single virtual access network that manages available radio resources in a globally optimal way. However, this approach does not investigate the gains from cooperation for each individual network, which determine the incentives for cooperation they have. We stress that apart from that related work does not focus centrally on the performance-oriented incentives that can motivate cooperation, which is the focus of the current paper. Rather, one line of work investigates approaches for improving the performance in wireless networks, whereas another line of work considers approaches for inducing cooperation.

Relay nodes can be used to mitigate the performance anomaly of 802.11. Lue and Lin (2006) propose a centralized protocol where the access point assigns relay nodes. Feeney et al. (2007) suggest a protocol where nodes increase their performance by replacing one low-rate transmission with a sequence of two high-rate transmissions. Bahl et al. (2008) propose a system where high-rate nodes opportunistically turn themselves into repeaters for low-rate nodes when they expect that it will be beneficial for all parties. The nodes are assumed to cooperate to achieve a common goal. Another approach is to aggregate the capacity of all the access points and use load balancing mechanisms in order to maximize the network performance (Kandula et al. 2008). All the above works focus on a single network, while we focus on the co-existence of self-interested WLANs that do not act towards achieving a common goal. Another direction tries to implement time-fairness by minimizing the time that low-rate transmissions use the shared wireless channel (Tang & Guttag 2004). However, this method has the disadvantage of being unfair towards low-rate links.

MANETs is a field where cooperation is important since nodes act in their own interest. However, related work focuses on ways to enforce cooperation either using virtual currency (Battyan & Hubaux 2003) (Crowcroft et al. 2003) or punishments (Buchegger & Le Boudec 2002) (Anderegg & Eidenbenz 2003). A key idea and motivation for our work is that such mechanisms are not required in the case we study, when performance improvements alone can provide sufficient handover incentives. Finally, our prior work (Fafoutis & Siris, 2010) has investigated resource sharing incentives between self-interested Wireless Mesh Networks (WMN). That work considered cooperation incentives in multi-hop WMNs, whereas the current paper investigates the handover incentives in the case of single hop WLANs.

6. Conclusions

Even in competitive environments where each party acts at its own self-interest, it is shown that there are cases where serving the clients of the neighboring access point, that belong to a different self-interested WLAN, can yield benefits to both parties. As a result, this performance gain raises incentives that can motivate cooperation without any agreement that includes monetary exchange or other form of cooperation. The proposed revised model is able to approximate the throughput in both the case of downlink and uplink traffic. Thus, it can be used in order to predict whether the handovers are expected to be beneficial and estimate the expected gain. The accuracy of the model is verified through simulations. The simulations suggest that the model may misestimate whether the cooperation is beneficial. However, misestimations appear in scenarios where the gain is marginal. Hence, the small number of false positives and false negatives do not affect the long-term benefits of handovers and the reliability of the model.

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