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Selecting Vertical Handover Candidates in IEEE 802.11 Mesh Networks

Sven Wiethoelter and Adam Wolisz
Telecommunication Networks Group
Technische Universität Berlin
Einsteinufer 25, 10587 Berlin, Germany
{wiethoel, wolisz}@tkn.tu-berlin.de

Abstract

The IEEE 802.11 working group currently integrates the option of mesh networking into its standard for WLANs. In addition to WLAN meshes, future wireless networks will be expanded by multiple heterogeneous access technologies such as UMTS and WiMax. These technologies differ greatly regarding medium access scheme, network capacity, QoS support, choice of data rates, and other various parameters such as power consumption and AAA aspects. Even though current research focuses on different network access selection and handover strategies maximizing the utilization for such a heterogeneous network, it is still an open issue how to select "inefficient" mobiles as vertical handover candidates. This work presents a novel scheme for the selection of handover candidates which is exemplarily discussed for an IEEE 802.11 WLAN mesh. After exploring the design rationale of the decision metric, simulation studies show the impact of single and multiple handovers on remaining users in the cell.

1 Introduction

Today's access networks differ greatly regarding coverage area, supported degree of mobility, and user data rates. Single WLAN access cells, for example, can offer high data rates in small coverage areas without any mobility support. Contrary, UMTS supports high mobility with large coverage but significantly lower data rates. As a result, combining different access technologies is a very promising approach to deal with various conditions such as user mobility, different traffic patterns, and QoS requirements.

Originally, the design of WLANs emphasized data service support in contrast to cellular networks focusing on voice services. This segregation is no longer applicable: Nowadays, WLANs and cellular networks have to support a complex mix of services. Furthermore, modern user devices are equipped with multiple network interface cards (NICs) and are thus able to use either of several available access technologies. Additionally, access providers extend the range of their products: it becomes quite common that a single provider is offering access to cellular and WLAN networks as well as to other technologies. Finally, the cheap extension of WLAN networks by so-called meshes [4] became a recent trend. There, the access cells are interconnected by a wireless mesh backbone with portals to the Internet.

The issue of access technology selection becomes more and more interesting, as it is no longer uniquely determined by either contract with the service provider or by the type of used service. For example, it might be attractive to relocate a voice user holding a call in a coffee shop from the cellular system to WLAN—in order to release the cellular capacity for other users. On the other side, if the cellular network has enough capacity, it might be interesting to shift a voice user from WLAN to free more capacity for data transfer.

Lots of research effort has been placed in the area of network selection and handover strategies for heterogeneous networks, recently. All approaches target to identify costs and revenues for each access network by combining certain input parameters to cost functions. These input parameters are nothing else than metrics reflecting criteria for a performance comparison of one specific aspect (such as load or QoS conditions). Most commonly, literature considers parameters ranging from users' preferences and QoS conditions, the load of access networks, the power consumption of network interface cards, and monetary costs. Other work focuses on the concatenation of these parameters to cost functions or other comparable decision models. A detailed classification of such decision models is given by Kassar et al. in [6].

Historically, Wang et al. [9] were the first who used a cost function for handover decisions in a heterogeneous network. This early work applied a linear combination of offered bandwidth, power consumption, and costs, whereby the natural logarithm was used as normalization function.

Even more recent work in the area of access selection

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and handover strategies for heterogeneous networks such as [2, 11] considers only the load of a radio cell (in terms of throughput or number of users). Although Cesana et al. [1] incorporated the interference between users in their network selection approach, the suitability of a traffic stream for a certain access network has remained an open issue when focusing on the load aspect.

Based on these insights, we introduce a novel decision metric that considers the efficiency of the occupied airtime for transmissions on the wireless channel. This work shows how the metric can be used for the identification of users who purely occupy the resources and are thus candidates for removal from a WLAN mesh. Additionally, we show how this metric can be used to predict the impact of potential new users on those already present in the WLAN access cells. An extended version of this paper can be found at [10].

The paper is structured as follows. Firstly, Section 2 describes the system model and discusses the proposed cost function for WLAN meshes. We discuss the usage of the novel metric for handover purposes in Section 3, while Section 4 presents the results of the simulation studies. Finally, conclusions are drawn in Section 5.

2 System Model

The system under study consists of a WLAN mesh coupled to a second heterogeneous access technology (denoted as "AT_2"). Thereby, the access cell of the WLAN mesh is completely within the coverage area of AT_2. We assume that all mobile terminals are equipped with a network interface card for each access technology such that they can perform vertical handovers.

Secondly, we assume that each access network has an own cost function reflecting the effort and the revenue serving a specific user who belongs to a certain traffic class.

For the handover decision process, the involved access networks are divided into two conceptual parts, namely the originator and the recipient network. In principal, there exist three general concepts regarding the placement of the handover decision. This can be realized within the originator network, the recipient network, or by a separate arbitration entity.

In the following, we discuss the outstanding tasks for a handover if the decision is made in the originator network. In this approach, the originator network firstly identifies potential handover candidate(s), secondly estimates the gain due to the potential handovers, thirdly requests cost function value estimates from the recipient network via appropriate means of signaling, fourthly compares candidates' cost function values within originator and recipient network, and finally decides for or against a vertical handover for each candidate.

Contrary, the recipient network firstly estimates the cost function value for each potential handover candidate currently served by the originator network, and secondly assesses the impact of a handover on other users.

As described above, we assume to have a cost function for each access network. For every user i in the WLAN mesh, the proposed cost function separates into two parts, considering the costs in the wireless access cell (c_A) as well as the costs in the wireless backbone (c_B):

$$c_{mesh}(i) = c_A(i) + c_B(i), \text{ with } c_B(i) = \sum_{n=1}^{\#hops} c_n(i) \quad (1)$$

Conceptually, c_B is represented by the sum of costs over all hops within the mesh backbone. Since this work concentrates on the novel decision metric, we focus on the cost function of the access cell, i.e., we assume c_B to be identical for all traffic flows in a first step. A detailed design of c_B is subject to future work.

The cost function of the WLAN access cell reflects the load in the cell, the utilization of allocated resources, and the QoS level for every user:[1]

$$\begin{aligned} c_A(i) &= \omega_1 \frac{t_a(i)}{\Delta t} + \omega_2 D(i) + \omega_3 QoS(i) \\ &\text{with} \sum_{k=1}^{3} \omega_k = 1 \end{aligned} \quad (2)$$

While $t_a/\Delta t$ is the occupied airtime on the channel in relation to measurement interval Δt, D represents the novel (normalized) decision metric evaluating the resource utilization on behalf of each traffic stream. The QoS parameter separates into several parts dependent on the requested service. Here, we distinct dependent on different QoS classes. For VoIP, it would consist of the end-to-end delay, jitter, and packet loss (normalized by their maximum tolerable values).

A handover for user i from the WLAN mesh to AT_2 takes place, iff

$$c_{mesh}(i) > c_{mesh}(j) \;\; \forall \text{ users } j \neq i \quad (3)$$

$$c_{mesh}(i) > c_{AT_2}(i) \quad (4)$$

Eq. 3 represents the identification of potential handover candidates within the WLAN mesh, i.e., the selection of the user with the highest cost function value. Eq. 4 describes the comparison of candidate's cost function value in the WLAN mesh and AT_2. Only in case that his value is significantly better in AT_2, a handover will be triggered. This part is indispensable, since serving the user with the highest costs in the WLAN mesh may still be cheaper than putting him into AT_2.

[1] Note that the cost function is easily extendable by other parameters reflecting the costs of the handover process itself, e.g., by considering the QoS degradation for the user, or the increased signaling load.

3 Inefficiency Metric

The goal of the proposed metric is to reflect the total utilization of allocated resources. This goal leads to the key question how to identify the parts (e.g., certain users or traffic flows) that contribute to the load in the access network drastically but benefit only marginally from these expenditures. Such behavior is denoted as "inefficiency" in the following.

In radio technologies such as WLAN, the load evoked by a user depends on various factors such as path loss, fading, and interference. In order to maximize the total number of users in the system without violating their QoS constraints, we follow the approach that the most "inefficient" users are selected as handover candidates.

Assuming ideal conditions (i.e., no path loss, collisions, packet errors, etc.) results in transmissions evoking the lowest possible load on the channel. Contrary, all means for error control and adaptation to channel conditions (e.g., rate adaptation, retransmissions) lead to an increase of the load on the wireless channel in real systems.

The design goal for the decision metric is to find a measure for the expenditures required to deal with these realistic conditions. It consists of two parts: the surcharge ζ and the overhead factor ϱ. While the surcharge is a measure for additional expenditures required for error control and correction, the overhead factor allows for an evaluation of different data packet sizes regarding their suitability in WLANs. In the following, both parts as well as their composition to the final inefficiency metric are discussed in detail.

3.1 Surcharge

This part is derived from the very basic definition of efficiency: In engineering, efficiency is usually defined as relation of system's output ϑ to the overall effort ψ one has to invest:

$$\eta = \frac{output}{effort} = \frac{\vartheta}{\psi} \quad (5)$$

Efficiency η can range in the interval $[0, 1]$, whereby effort values much larger than output values ($\psi >> \vartheta$) lead asymptotically towards efficiency values of zero.

The design rationale behind this part is to identify terminals with smallest efficiency values as handover candidates. However, it may be difficult to distinguish between two very small efficiency values near zero although the corresponding difference of effort values may be significant. Hence, the reciprocal is applied to enable comparability.

$$surcharge\,\zeta = \eta^{-1} = \frac{\psi}{\vartheta} \quad (6)$$

In WLANs, the effort ψ for a single transmission of an MPDU depends on the state of the wireless channel, the choice of a modulation scheme, the collision level as well as the number of retransmissions. All these parts have impact on the effort for a transmission in a way that they affect its duration. Thus, it is straightforward to consider the duration for a complete transmission sequence in order to determine its effort (Eq. 7). There, the number of trials represents the (re)transmissions that have been required to ensure the delivery of the MSDU.

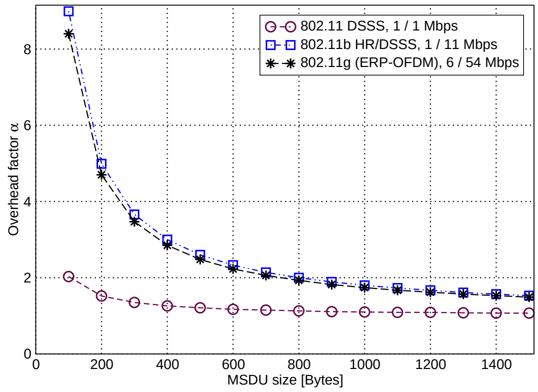


Figure 1. Overhead factors of 802.11/b/g

$$\psi = t_a = \sum_{i=0}^{\#trials} \Delta t_i \quad (7)$$

For each trial, Δt_i represents the amount of time that the wireless medium is occupied (or reserved, in case of inter-frame spaces and NAV settings):

$$\Delta t_i = t_{IFS} + t_d(Rate_i) + t_{ack} \quad (8)$$

This includes the whole transmission sequence consisting of the inter-frame spaces DIFS or AIFS and SIFS (t_{IFS}), the duration t_d of the complete data frame "on air", where the data part is encoded with a certain modulation scheme $Rate_i$ and the acknowledgment t_{ack}.

Secondly, we define system's output at MAC level as the smallest possible duration for the whole transmission that would be required in case of an ideal error free channel (Eq. 9).

$$\vartheta = \Delta t_{opt} = t_{IFS} + t_d(max\,Rate) + t_{ack} \quad (9)$$

Note that the output definition includes the duration of the whole data frame when the data part is encoded with the highest modulation $max\,Rate$ and only the single transmission attempt. Thus it serves as a reference case that implies the smallest possible effort.

3.2 Overhead Factor

While the surcharge is a measure for the efficiency regarding the transmission of MSDUs, it does not tell anything about the suitability of WLANs to transport these

MSDUs with their specific size. IEEE 802.11 introduces a fixed amount of overhead (PHY framing, inter-frame spaces and immediate ACK) for one transmission regardless of the MSDU size. Thus, the smaller the MSDU size, the less becomes 802.11 optimally utilized. To accommodate this behavior, we introduce the overhead factor as

$$\alpha = \frac{\Delta t_{opt}}{\Delta t_{MSDU_{opt}}} \tag{10}$$

While Δt_{opt} is again the smallest possible duration for a frame exchange (Eq. 9), Δt_{MSDU} represents the duration of the bare MSDU assuming the highest modulation scheme.

Figure 1 displays the overhead factors for different MSDU sizes and three different 802.11 PHYs (figure's legend box specifies PHYs' basic / data rate, other parameters according to [3]). 802.11 and 802.11b curves clearly show that the higher the data rates, the higher is the overhead especially for small MSDU sizes such as VoIP (e.g., 200 Bytes in case of G.711-coded speech and a packetization of $20\ ms$). The overhead values of 802.11g ERP OFDM PHYs are slightly lower than the 802.11b curve. This results from the fact that 802.11g ERP OFDM comes up with smaller slot times, shorter PLCP preamble and header as well as a higher basic rate of 6 Mbps.

3.3 Metric Composition

In order to allow the handover candidate selection among users with heterogeneous traffic patterns, overhead factor α and surcharge ζ are combined to the inefficiency metric:

$$D = \alpha\zeta \tag{11}$$

By calculating respectively measuring output ϑ and effort ψ over fixed-size intervals, one is able to compute the metric value over multiple transmissions / larger time scales. Within this work, an interval size of $100\,ms$ were applied.

4 Impact of Inefficiency Metric

Even in recent studies, handover or access selection decisions in heterogeneous networks are performed for the WLAN part on the basis of SNR values, e.g., in [11]. In such approaches, terminals with lowest SNR values are candidates for a handover. For complete homogeneous traffic patterns, SNR may be indeed an appropriate measure to judge the efficiency of transmissions. Under such conditions, both metrics—SNR as well as inefficiency metric—are expected to decide for the same stations as handover candidates.

Contrary to SNR, the inefficiency metric includes much more knowledge, e.g., the applied data rate for a transmission, the number of retransmissions, the packet length as well as a factor for the overhead. Thus, the inefficiency metric has a great potential for adoption to handover decisions in case of heterogeneous traffic mixes.

To allow for a qualitative comparison with SNR-based decisions, this work concentrates on a homogeneous traffic pattern. A complex mix of different services is subject to future work.

4.1 Goals of Investigation

Firstly, the simulation study identifies candidates that contribute to the load in the access network drastically but benefit only marginally from these expenditures. Secondly, we identify the impact of the selection scheme on users remaining in the WLAN cell, if a single candidate performs a handover from WLAN to AT_2. Thirdly, we are interested in the impact of multiple handovers according to our approach: There, we handover several candidates from WLAN to AT_2, while the same number of users (with the same service type) are put from AT_2 to WLAN.

4.2 Set of Experiments

For the above goals, a set of three experiments has been performed: the max. #nodes, the reduced, and the replaced set(s).

The first experiment determines the maximum number of nodes such that the WLAN network is loaded (but not saturated) in a way that the QoS constraints of at least one node are violated.

Secondly, we show the impact of a single handover from WLAN to AT_2 when choosing the most ”inefficient” WLAN user. This experiment is called ”reduced set” since the total number of WLAN users decreases. In comparison to the maximum number of nodes, this experiment gives an idea about the approximate range of improvements due to the single handover of the most ”inefficient” user.

Thirdly, we study the impact of multiple handovers according to our strategy. There, we conduct a replacement of nodes based on the results of the ”max. #nodes” experiment. Under replacement, we understand here that a node with a high metric value is triggered to perform a handover from WLAN to AT_2, while the WLAN network accommodates another node (either due to a handover from AT_2 or a new, arriving user). Here, it is assumed that this new node is present near the AP with a distance of $10\ m$ and represents the same user type as the one put from WLAN to AT_2. This third experiment is conducted with one to three replacements in total.

4.3 Simulation Scenario

The scenario under study consists of a WLAN mesh interconnected to a heterogeneous access technology AT_2. It is assumed that AT_2 provides full coverage in the region of interest and is capable to serve all arriving users. The WLAN mesh consists of a wireless backbone using 802.11a and a single hotspot that covers only a certain part of the area, e.g., like a departure lounge in an air-port.

The considered hotspot is represented by an IEEE 802.11g AP that is 11e-capable by providing EDCA functionality. We assume to have VoIP users only, which are equally distributed over the area of interest. Users are stationary and equipped with AT_2 as well as with WLAN devices. The latter applies 802.11g Extended Rate Physicals (ERPs) with OFDM modulation—from 6 up to 54 Mbps. The 802.11e/g parameters were chosen according to [3] (TXOPLimits were set to zero such that a single transmission per medium access attempt is performed).

To take into account that radio signals are not only affected due to path loss but also due to multipath propagation, we apply the two-ray ground reflection model of ns-2, a Ricean fading model, the rate adaptation scheme AARF, and a novel SINR model. Models' details are described in [10].

4.4 Node Placement and Traffic Model

In the simulation scenario, WLAN VoIP nodes are distributed equally over the area of interest, which has a shape of a quarter circle. There, the AP is located at the corner of the considered environment, such that no hidden nodes appear.

All wireless stations have a VoIP call with a wired node outside the WLAN. The delay between the AP of the WLAN access cell and the wired nodes was set to $100\,ms$. All stations use an exponential ON/OFF model with mean ON and OFF durations of $1.004\ s$ and $1.587\ s$ [5]. During the ON periods, voice packets are generated according to the ITU-T codec G.711 with a packetization of $20\,ms$, i.e., each voice flow has a $64\ kbps$ peak rate with $160\ Byte$ audio packets.

4.5 Metrics and QoS Constraints

4.5.1 Surcharge

Each transmitting station determines its surcharge value over $100\ ms$ only if there have been any transmission attempts during this interval. Since this work considers the same VoIP traffic pattern for all nodes, the overhead factor is just a constant value. Thus we focus on the surcharge part of the inefficiency metric in our simulation studies.

4.5.2 Application-level Losses

In order to assess the quality of the VoIP calls, we measure the loss of audio packets on application level over certain intervals. A loss can either occur due to lost or late packets. A packet is considered to be late if it arrives after a maximum network delay of $150\ ms$ (similar to [7]) at the receiver such that it cannot be played out anymore.

4.5.3 QoS Constraints

For every single VoIP call, the quality should stay on an acceptable level. "Acceptable" thereby means that a certain boundary for application level losses—consisting of packet losses and late packets—is not violated.

With Packet Loss Concealment (PLC) schemes and one-way delays up to $200\ ms$, random losses of up to 5 percent for G.711 are acceptable [8, p. 38, Fig. 29]. If five or more percent of the VoIP packets are lost, i.e., they have been dropped or they arrive with a network delay larger than 150 ms, the perceived quality is assumed to be temporary lousy. The interval over which this criterion is evaluated has been set to 4 seconds (rationale in [10]).

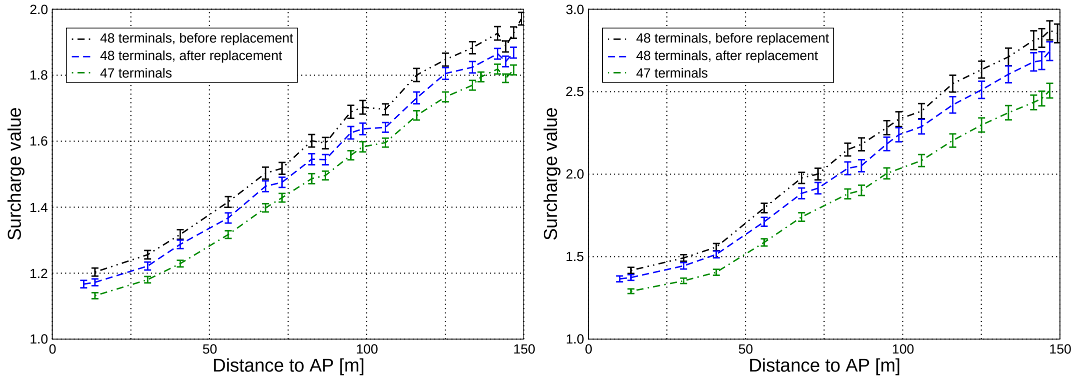
In our work, the QoS boundary is defined as follows: If the perceived quality is temporary lousy in 10 or more percent of the overall number of intervals, the quality degradation of the complete call is defined as not acceptable anymore.

4.6 Results

All surcharge results have been evaluated by batch means analysis and mean values are plotted with their 95 percent confidence interval.

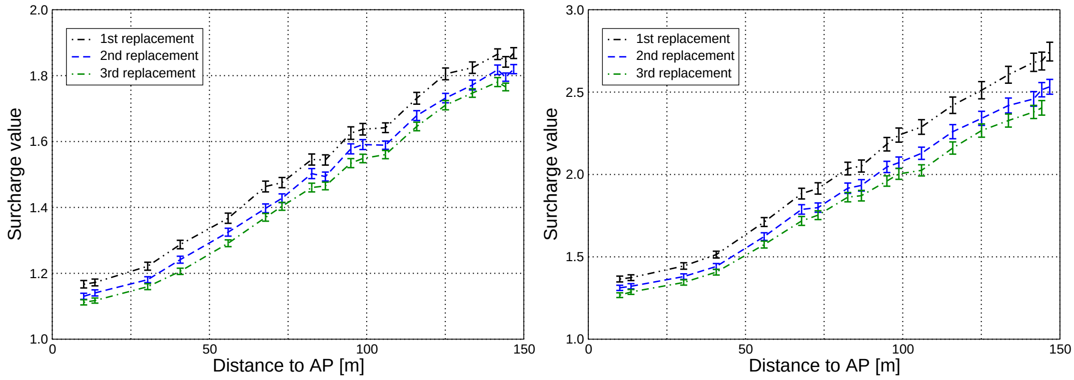
In the first experiment, the maximum number of nodes has been determined such that the QoS constraints of at least a single node are violated. This is achieved with 48 VoIP nodes in total. Table 1 shows the cumulative probability of having five or less percent of application losses for all experiments in up- and downlink. While the QoS-boundary is violated for all nodes in the downlink, the losses depend greatly on the distance between AP and STAs for the uplink, where boundaries are crossed for far nodes, only. This effect results from the asymmetric traffic distribution between AP and STAs and is discussed in [10] .

After identifying the operational point of the network where QoS constraints of several clients are being violated, the second set of experiments shows the impact of a single handover. There, the handover candidate was selected according to the novel strategy of selecting the most "inefficient" user. After this single handover, i.e., 47 active VoIP nodes in total, the packet loss is below 5 percent in more than 90 percent of the evaluation intervals for downlink and uplink direction, respectively (Table 1). Thus, QoS constraints as defined in Section 4.5.3 are met for all 47 nodes due to a single handover following the efficiency-aware selection approach.



(a) Downlink (b) Uplink

Figure 2. Comparison of surcharge values from all three experiments



(a) Downlink (b) Uplink

Figure 3. Surcharge values after one, two, and three replacements

Now, let's consider the effect of a single replacement, i.e., the most inefficient node is triggered to perform a handover from WLAN to the AT_2 network, while the WLAN network accommodates another VoIP node (with a distance of 10 meters to the AP). Figure 2 shows the surcharge values in up- as well as downlink direction for all three experiments. There, the surcharge values increase with larger distances between nodes and AP. This result was expected since the probability for lower data rates and higher number of retransmissions increases with the distance. All these impacts are now unified in the single surcharge metric. Not surprisingly, the "max. #nodes" experiment results in highest surcharge values for all nodes, while the single replacement experiment leads to a significant reduction: the surcharge values drop by around 2.3 to 3.9 percent (downlink) and 2.9 to 5.9 percent (uplink). Lowest surcharge values are gained with the "reduced set" experiment, where the most inefficient node was selected as handover candidate. There, the surcharge values of all other remaining nodes drop by 3.6 to 7.9 percent in the downlink and 3.5 to 12 percent in the uplink compared to "max. #nodes" results.

It attracts attention that surcharge values are higher for the up- than for the downlink direction. This stems from the asymmetric traffic conditions, which actually is in line with previous results. The extended version of this work [10] describes this effect in detail.

The positive impact of further replacements is displayed in Fig. 3, again for up- as well as downlink. While the second replacement leads again to a relatively large decrease, no significant improvement was gained with the third replacement (i.e., confidence intervals of 2nd and 3rd replacements overlap at several distances).

Lastly, we consider the impact of replacements on users' QoS. While the first replacement does not improve the application losses greatly for up- and downlink, it is the second replacement that avoids a violation of QoS constraints. From Table 1, we can observe that less than 5 percent losses occur in 90 percent of the intervals for up- as well as downlink direction.

Now, the third replacement brings users' QoS up to level of the reduced-set experiment, which means that we gain comparable quality although there are 48 instead of 47

Table 1. Quantiles at 5-percent packet loss

	Uplink							Downlink						
	Distance to AP [m]							Distance to AP [m]						
	14	49	83	116	134	144	149	14	49	83	116	134	144	149
max. #nodes	1.0	1.0	0.98	0.91	0.89	0.88	0.88	0.89	0.89	0.89	0.88	0.88	0.88	0.88
reduced set	1.0	1.0	0.99	0.95	0.93	0.93	—	0.94	0.94	0.94	0.93	0.93	0.93	—
1st replacement	1.0	1.0	0.98	0.93	0.90	0.90	—	0.91	0.91	0.91	0.90	0.90	0.90	—
2nd replacement	1.0	1.0	0.98	0.94	0.93	0.92	—	0.93	0.93	0.93	0.93	0.93	0.93	—
3rd replacement	1.0	1.0	0.99	0.95	0.94	0.94	—	0.95	0.94	0.94	0.94	0.95	0.94	—

nodes. Interestingly, there are only small differences in QoS values between 2nd and 3rd replacement. This is directly in line with the surcharge results, where confidence intervals overlap such that there's no significant difference at certain points anymore. From the replacement study we observe that a non-significant impact of a replacement on the surcharge also implies only marginal differences in users' QoS in case of VoIP traffic.

5 Conclusions and Future Work

This work extends handover decisions being based on the measured load for every user. The inefficiency metric follows a novel approach in which most ”inefficient” users are selected as handover candidates. ”Inefficient” thereby refers to parts contributing to the cell load greatly but benefiting only marginally from this effort. The two parts of the decision metric are discussed in detail by focusing on 802.11 mesh networks. Firstly, proof-of-concept simulations are used to document that the novel metric is suitable to select most ”inefficient” users. Secondly, simulation results show the improvements for users remaining in the WLAN access cell, after performing a handover of the most inefficient candidate. Finally, we study the impact of our scheme in case of multiple handovers, where ”inefficient” WLAN users are replaced by suitable candidates from other heterogeneous access networks.

As future work, we firstly consider the investigation of our approach with a mixture of elastic and inelastic traffic together with a quantitative comparison of other decision metrics like RSSI and SINR. Secondly, we will focus on cost metrics for the wireless mesh backbone and the concatenation of its cost function.

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