Optimized Flow Management using Linear Programming in Integrated Heterogeneous Networks

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***Abstract*—There have been tremendous advances over the past decades when it comes to wireless access technologies. Nowadays, several wireless access technologies are available everywhere. Even mobile devices have evolved to support multiple access technologies (e.g., 3G, 4G or WiFi) in providing the best possible access to the Internet. However, all of these devices can communicate using one access technology at a time. There is a need of the integration of all these access technologies to cooperate and work simultaneously in a heterogeneous environment from which both the end users, as well as, the mobile operators can benefit. This paper investigates how to tackle the simultaneous usage of wireless access technologies in the downlink. For this purpose, a practical example of 3GPP LTE and non-3GPP WLAN integrated heterogeneous network is considered. Furthermore, a novel decision mechanism is proposed, that focuses on optimizing the flow management of user traffic flows based on a mathematical formulation of the system. The mathematical model is implemented using the Linear Programming techniques. The paper demonstrates the gains that are achieved from using such innovative decision mechanism, as well as, the benefits that arise from the simultaneous usage of wireless heterogeneous accesses.**

Keywords: ***LTE and WLAN interworking, User QoE optimization, Linear programming, Access link modeling***

I. INTRODUCTION

4G communication networks are purely IP-based, and characterized by independent drives, such as: users, network operators, and service providers, etc. Due to the maturity of the current communication paradigms, there is no point in highlighting the importance of heterogeneous wireless technologies and their co-existence in the future wireless access networks. When it comes to heterogeneous wireless technologies, one can discern various prevailing standards in the current communication market, such as 3GPP, non-3GPP, 3GPP2, etc. Both 3GPP and non-3GPP are of core importance, however it is common conception that most of the non-3GPP technologies need less investment and operation & maintenance cost compared to 3GPP technologies. Furthermore, the widespread usage of non-3GPP wireless access technologies, like IEEE 802.11 has shown its practical usefulness in many environments. Now, that the market is ready to accept both 3GPP and non-3GPP technologies, this provisions that end consumers should be enabled to make efficient use of the services extended through both technologies. Even more, the 3GPP standards has already come up with such integration standards [13].

The System Architecture Evolution (SAE) 3GPP specified allows mobile users to roam between 3GPP and non-3GPP access technologies. In order to provide users with seamless mobility, Proxy Mobile IPv6 (network based mobility) and Dual Stack Mobile IPv6 (host based mobility) have been proposed [13]. The 3GPP SAE architecture, however, has certain limitations when it comes to supporting multi-homed users. This implies that a user can be associated with one of the available access networks but cannot connect to more than one network simultaneously.

The focus of this work is to firstly investigate how the multi-homing support can be realized in 3GPP SAE architecture. Secondly, how the network operators can make an optimum use of aggregated bandwidth resources and network diversity in a multi-homing scenario through the flow management. The rest of the paper is organized as follows: related work has been discussed in Section II, Section III describes how the current 3GPP SAE architecture can be extended to provide users with multi-homing support. Section IV describes the importance of flow management function in a heterogeneous network, and Section V explains the linear programming technique to do optimized flow management operation. Finally, Section VI provides the proof of concepts through the discussion of simulation results of an investigated realistic scenario.

II. RELATED WORK

A number of research studies can be found making use of cross-layer techniques and soft handover to optimize handover cost in terms of packet delay and loss in heterogeneous networks. For example, Song and Jamalipour [2] describes an intelligent scheme of vertical handover decisions in selecting the best handover target from the several candidate heterogeneous networks. Several other proposals have been made to improve the performance of cellular and 802.11 networks. Song et. al. [3] has discussed admission control schemes to improve the performance of integrated networks. Fei and Vikram [5] proposes a service differentiated admission control scheme based on semi-Markov chain which is although very accurate but has high computational complexity. Similarly, Zhai et. al. [6] has shown that by controlling the collision probability with the help of input traffic rate of users, the maximum throughput can be achieved by keeping 802.11 network in non-saturated state. Other studies are focused on developing solutions for

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load balancing in the integrated heterogenous networks. Such a proposal can be found in [7] where policy based load balancing framework has been presented to effectively utilize the aggregated resources of loosely coupled cellular/WLAN network. In this work, we explore the practical limits of achievable performance in a heterogeneous network scenario by going down to the MAC layer functionalities of involved access technologies. The goal is to maximize the spectral efficiency of network bandwidth resources and fulfill the application QoS requirements at the same time. In contrast to other studies, we provide an analytical solution to the problem which adapts time varying channel conditions of the user and dynamically decides the best network paths for user traffic flows in order to achieve system wide optimized performance and improved user QoE. The focus of this work is, however, restricted to the downlink of access technologies.

III. Network simulation model

This work follows the proposal of 3GPP specifications in the integration of 3GPP access technology (namely, LTE) and trusted non-3GPP access technology (namely, legacy WLAN 802.11g) where host based mobility solutions, i.e., Dual Stack Mobile IPv6 is considered. For this purpose, a simulation network model has been implemented using the OPNET [14] network simulator. This includes the detailed implementation of LTE network entities following the 3GPP specifications. As per 3GPP proposal the home agent (HA) function is located at the Packet Data Network (PDN) gateway. The remote server acts as a correspondent node (CN) from where mobile users access application services like VoIP, video, HTTP and FTP (see Fig. 3). A comprehensive description of this heterogeneous network simulator can be found in [9].

It should be noted that our focus is only on the downlink access for LTE and WLAN. This implies that no uplink transmissions are performed for WLAN during the whole simulation time. Instead uplink traffic (e.g., TCP ACK packets etc.) is transmitted by the user through LTE access link.

IV. Flow Management

In the developed simulation environment, a user can communicate simultaneously through 3GPP access technology, i.e. LTE, as well as non-3GPP access networks, i.e., WLAN. The question still remains how a network operator or a user can make use of the two network paths from two access technologies. The answer is to introduce a flow management function at the home agent. The flow management function makes use of the MIPv6 extensions and allows to control the user data rate on each network path. In general, there are two options of managing traffic flows for a multi-homed user. The first option is to carry one complete application traffic flow over one path of choice, this is known as "traffic flow switching". The second option is to divide the traffic flow into several smaller sub-flows where each sub-flow is carried over one network path. This will be called "traffic flow splitting".

If flow management is performed in properly a considerable improvement in network capacity and user satisfaction can be achieved. That is why the decision engine of the flow management function which controls the user data rate over the network paths is of core importance. In order to attain the goals of optimized network performance, the decision engine needs to know the precise information of the available network resources and the user demands. Once this information is available, the decision engine, with the help of proposed mathematical techniques, can optimally assign network resources to the users fulfilling their demands while making use of all available network paths. Though in this work the decision engine of the flow management function is located at the home agent, this may reside at any point inside the core network according to the network hierarchy demands.

The amount of network resources of a wireless network are determined from the designed parameters like frequency spectrum, transmission technology, antenna gains etc. Therefore each network has a fixed amount of network resources and the network performance itself depends on the fact with what (spectral) efficiency these resources are utilized. In order to achieve higher data rates a network resource scheduler should select those users who can attain high spectral efficiency and therefore need less network resources per unit data rate. In this work we adapt the term "network path cost" for the required network resources per unit data rate. For a user, its network path cost can be accessed through cross layer information from the MAC layer of the corresponding access technologies. In the following subsections, it is shown how the network path cost can be computed for users in WLAN and LTE networks.

A. Network path cost for WLAN

Consider a scenario where a WLAN access network consists of a station associated with an access point. Assume that the station is just receiving a downlink traffic flow from the access point and does not transmit anything in the uplink. In this way, there is no contention for medium access. The transmission of one data frame with RTS/CTS enabled takes T_S seconds including the exchange of control frames such as RTS/CTS, SIFS (Short Interframe Space), DIFS (DCF Interframe Space), and ACK frames, where

$$T_S = T_{backoff} + T_{DIFS} + T_{RTS} + T_{CTS} + T_{data} + 3 \cdot T_{SIFS},$$

$$T_{backoff} = \frac{W_{min} - 1}{2} \cdot T_{slotTime},$$

$$T_{DIFS} = T_{SIFS} + 2 \cdot T_{slotTime}$$

All components of T_S except T_{data} can be found in the 802.11 standards. The value of T_{data} can be computed based on the PHY speed of transmission, i.e., $T_{data} = \frac{\sigma}{\varphi}$, where σ is the data frame size in bits, and φ is the PHY transmission speed in [bit/sec]. Accordingly, the maximum downlink capacity η can be estimated as follows: $\eta = \frac{\sigma}{T_S}$ [bit/sec].

It is clear that 802.11 MAC follows the Time Division Multiple Access (TDMA) like scheme, where users share the wireless access medium for short periods of time. Considering resource allocation time interval of 1, a user needs medium access for a fraction τ of the interval to achieve a unit data rate of 1 bit/sec. τ is actually the network path cost whose value directly depends on T_S, which is the delay experienced in transmitting one data packet of average size σ [bit] operating with PHY speed φ [bit/sec]. That is, $\tau = \frac{T_S}{\sigma}$

B. Network path cost for LTE

In contrast to 802.11, LTE performs a managed scheduling of available bandwidth resources. The smallest unit of bandwidth resource is referred as a physical resource block (PRB) in the LTE specification. Based on the allocated frequency spectrum size, LTE has a certain number of PRBs. The LTE MAC scheduler residing at the eNodeB schedules these PRBs using a 1ms transmission time interval (TTI). The LTE MAC scheduler has a very complex way to assign resources to the associated users. Without digging into the details of the MAC scheduler operation, we focus on the last stage of resource assignment procedure in a certain TTI. On reaching that stage, the MAC scheduler already builds up a list of users which will be transmitting/receiving data in that TTI. For each user entry in the list, there is a corresponding value of the allocated number of PRBs, as well as the channel dependent Modulation and Coding Scheme (MCS) index. These two values are used to lookup the Transport Block Size (TBS) from a table defined in the 3GPP specifications [10]. This is a two-dimensional table, where each row representing one MCS index lists several values of TBS corresponding to the allocated number of PRBs. The obtained TBS value defines the size of the MAC frame transmitted to the user in that TTI. In this way, the user received throughput at the MAC layer in a certain TTI can be estimated if the TBS value for that user is known.

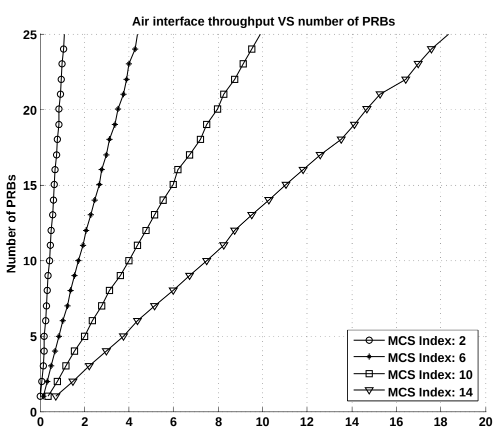

Fig. 1. Relationship of LTE air interface throughput and number of PRBs for different MSC index values [10]. Each curve represents one MCS index.

Fig. 1 shows that for a particular MCS index, the LTE throughput value has almost a linear relationship with the used number of PRBs. If described mathematically, this relationship can be used to determine the required number p of PRBs/TTI to achieve a certain data rate X [kbit/sec] for a user having MCS index i. That is

$$p = C_i \cdot X + K_i$$

C_i is slope of a straight line (as shown in 1) described in units of PRBs/kbps. K_i is the intercept at the y-axis and has units of number of PRBs. It can be noticed that C_i is the data rate dependent part, while K_i is the data rate independent part of network resource requirement for a user with channel conditions mapped to MCS index i.

V. Optimized network resource utilization

When the network path costs for a multi-homed user are known, the problem of optimal resource utilization can be solved using mathematical techniques. In this work, we prefer Integer Linear Programming (ILP) to solve this problem. This choice has been made due to several reasons. In ILP, the optimum solution is guaranteed for a correctly formulated problem, the problem can be extended or restricted by introducing appropriate constraints, it saves some additional implementation work by making use of already available linear programming solvers etc.

Given

- U — a set of users
- α_j — Data rate dependent part of the LTE link cost in PRBs per kbps for user j, for each $j \in U$
- β_j — Data rate independent part of the LTE link cost in PRBs for user j, for each $j \in U$
- γ_j — Cost of WLAN link in seconds per kbps for user j, for each $j \in U$
- δ_j — Minimum data rate (kbps) demand of a traffic flow destined to user j, for each $j \in U$
- Δ_j — Maximum data rate (kbps) allocation for a traffic flow destined to user j, for each $j \in U$
- Ω — Number of available PRBs for the LTE access network

Defined variables

- X_j — Size of sub-flow in kbps sent over the LTE access link to user j, for each $j \in U$
- Y_j — Size of sub-flow in kbps sent over WLAN access link to user j, for each $j \in U$
- Z_j — Auxiliary binary variable; its value for a user j is either 1 if $X_j > 0$ or 0 otherwise, for each $j \in U$

Maximize

$$\sum_{j \in U} X_j + Y_j$$

Subject to

1. $\sum_{j \in U} \alpha_j \cdot X_j + \beta_j \cdot Z_j \leq \Omega$
2. $\sum_{j \in U} \gamma_j \cdot Y_j \leq 1$
3. $\delta_j \leq X_j + Y_j \leq \Delta_j$ for each $j \in U$
4. $Z_j \leq X_j \cdot 10^{20}$ for each $j \in U$
5. $Z_j \geq X_j / \Delta_j$ for each $j \in U$
6. $0 \leq X_j \leq \Delta_j$ for each $j \in U$
7. $0 \leq Y_j \leq \Delta_j$ for each $j \in U$
8. $Z_j \in \{0, 1\}$ for each $j \in U$

Fig. 2. Mathematical model for the optimized resource utilization in algebraic form

Fig. 2 shows the formulation of the problem in algebraic form. The model defines U as the set of multi-homed users. Each element of this set has a number of input parameters, e.g. network path costs for LTE (α,β) and WLAN network (γ)

according to the user channel conditions in the corresponding network. The maximum and minimum range of user data rate demands (δ, Δ) which is based on the individual user application. The amount of available network resources in LTE (Ω) and WLAN (which is 1 second) are also considered as input parameters. The output parameters for each user in set U include the assigned data rate over the LTE network and the WLAN network paths (X,Y). It is obvious that the goal of this model is to achieve the highest possible spectral efficiency from the two network access technologies. The higher the spectral efficiency, the higher the network throughput. Hence, the objective is to maximize the user data rate over the two network paths, i.e., X and Y for every multi-homed user.

The model imposes eight constraints which are listed at the bottom of Fig. 2. The first two constraints ensure that the available network resources should not be exceeded when allocating the data rates for users. The third constraint dictates that the user data rate allocation should lie in the specified range. The 4th and 5th constraint determine the value of variable Z based on the X value. If there is a need, a user is allowed to receive its whole demanded data rate over a single network path as shown in constraint number 6 and 7. Constraint 8 is set in order to emphasis that Z is a binary variable which has value either 0 or 1.

It is assumed here that each user is running only one application. For a constant bit rate application, e.g., VoIP or video the minimum data rate is set equal to the maximum data rate in the model input parameters. For TCP based flows, these two values can be set according to the network operator's policy. It should be noted that the problem has been formulated in a way that it guarantees the minimum data rate for all users and then assigns an additional data rate up to the maximum data rate while optimizing the spectral efficiency of the access networks.

In the investigated scenario, the LTE coverage is available in the whole area of user movement while WLAN coverage is limited in a circular area of 100 meter radius around a hotspot. This implies the users always have LTE access available and WLAN coverage is only found in the vicinity of the hotspot (see Fig. 3). During the resource assignment process, the flow management function classifies users into the following three categories (i) users with LTE access only and running VoIP or video applications (ii) users with LTE and WLAN access running any type of application (iii) users running FTP or HTTP applications with LTE access only. Users in the first category must be assigned the required minimum data rate through LTE as there is no other access available for them. Users in the second category are multi-homed users whose data rate will be decided by the aforementioned mathematical model. For users belonging to the third category, they must get their traffic through the LTE path, however, it is not clear how much data rate should be allocated to them in order to achieve the optimized resource allocation objective. This issue is resolved by using the following work around: the users are assigned a WLAN network path cost greater than unity and they are put into the second category. The WLAN network

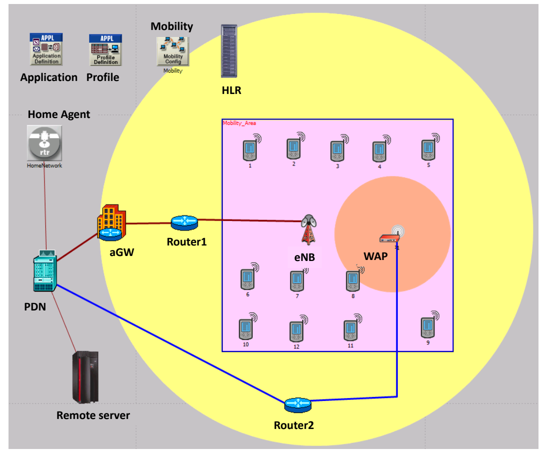

Fig. 3. Overview of the considered simulation scenario in the OPNET simulator. The large circular area shows the LTE network coverage and the smaller circular area shows the WLAN network coverage. The user movement is restricted to the rectangular area inside the large circle.

cost greater than unity will refrain the LP solver to assign any data rate for these users over the WLAN path while the data rate for the LTE path will be decided based on the global objective of the optimized resource allocation.

The resource assignment process by the flow management function is carried out periodically every 100ms in order to adapt to any changes in the user channel conditions. For this purpose user channel condition parameters are obtained through cross layer information from the base stations of the two access technologies. With the help these parameters, costs for each user network path is computed and fed to the above described mathematical model as the input arguments accompanied with the user data rate demands. As described earlier, the mathematical model is formulated using linear programming and solved using the C application programming interface (API) of ILOG CPLEX from IBM [15] which has been integrated inside the OPNET simulator by the authors. The output of this process consists of user data rates on each network path. These decided data rates are then implemented for each user through a traffic shaping function residing at the home agent.

VI. Simulation Results

This section shows the benefits of the proposed approach with the help of simulation results. For this purpose, two scenarios are considered. In one scenario, users do not make simultaneous use of LTE and WLAN access technologies. Instead the user traffic is completely handed over to WLAN as soon as the user enters in the hotspot coverage, otherwise all traffic takes its path through the LTE access. This is the default policy for a multi-homed user according to the 3GPP specifications and therefore it will be referred to as "3GPP HO" case. Whereas, the second scenario extends the 3GPP architecture to supporting the simultaneous use of wireless interfaces, this will be referred to as "Multi-P". In this case user traffic flows are distributed over the WLAN and the LTE

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TABLE I
SIMULATION CONFIGURATIONS

Parameter	Configurations
Total Number of PRBs	25 PRBs (5 MHz specturm)
Mobility model	Random Direction (RD) with 6 km/h
Number of users	2 VoIP, 1 HD video & 3 Skype video call, 2 HTPP, 4 FTP downlink users
LTE Channel model	Macroscopic pathloss model , Correlated Slow Fading [1]
LTE MAC Scheduler	TDS: Optimized Service Aware [8], FDS: Iterative RR approach
WLAN technology	802.11g, RTS-CTS enabled, coverage $\approx$ 100 m
VoIP traffic model	G.722.2 wideband codec, 23.05kbps data rate
Skype video model	MPEG-4 codec, 512kbps, 640x480 resolution, 30fps, play-out delay: 250 ms
HD video model	MPEG-4 codec, 1Mbps, 720x480 resolution,
HTTP traffic model	Pag size: constant 100KB, reading time: 12s
FTP traffic model	FTP File size: constant 10 MByte continuous file uploads one after the other.
Simulation run time	10^3 seconds,14 seeds, 98% confidence interval

access network. The traffic flow distribution policy is derived from the output of the optimization problem solved using linear programming. As a result, a user traffic flow is either sent over one network path with the least cost or it is split into two appropriately sized sub-flows each taking one network path to the destination. A reordering buffer at the receiver takes care of sub-flow aggregation and packet reordering in case of flow splitting.

Fig. 3 shows an overview of the simulation model implemented in OPNET. The system is populated with 12 users generating a rich traffic mixture of as shown in Table I. The users move within one LTE eNB cell, and within this cell one wireless access point (or hotspot) is present. It should be noted that in the “Multi-P” scenario the minimum data rate for FTP and HTTP users is assigned as 200kbps while the maximum data rate limit is set to a very high value of 25Mbps.

It’s worth mentioning here that in the “3GPP HO” scenario users make vertical handover of hard nature, i.e., the user disconnects completely from one network, and establishes a new connection to the other. Though MIPv6 keeps all IP layer connections alive through seamless handover, users might lose some buffered data on the previously connected network. On the other hand, the “Multi-P” scenario makes users use the WLAN when it is in the coverage, and can still keep the LTE connection and use it simultaneously. As a result, a bandwidth aggregation process of both access links is carried out.

Fig. 4 shows the spider web graph of the average number of successful file downloads per user. A spider web graph is a visualization technique that can show multiple results in one graph, and is used to compare the different scenarios. The graph in Fig. 4 has four different axes, each representing one application. Since all the axes represent the number of file downloads, the algorithm producing the larger shape has the best performance. In this case, it is clear that the “Multi-P” algorithm achieves the best results for all types of user traffic. The reason why TCP based applications accomplish less file downloads is twofold (i) higher TCP throughput helps them download more files as seen in case of FTP (ii) in case of

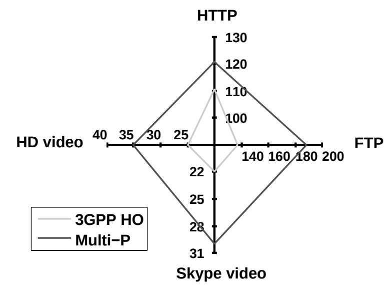
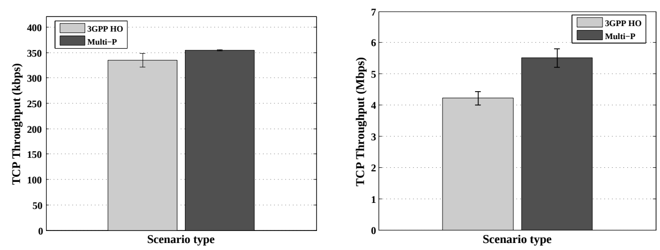


Fig. 4. Overview of downlink service performance. Average number of successfully downloaded files by a user.



(a) Average HTTP user throughput (b) Average FTP user throughput

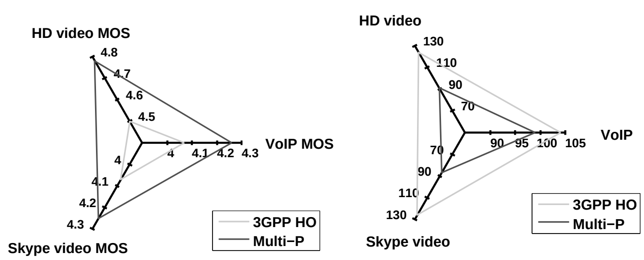
Fig. 5. TCP download throughput experienced by FTP and HTTP users

“3GPP HO” some TCP connections are aborted during the vertical handover due to excessive packet loss and sudden big changes in TCP round trip time. The second point is explained further in the following.

In “3GPP HO” scenario, when the users move from one access network to the other, the data buffered at the base station in the previous network is lost. This is because in the “3GPP HO” case users cannot keep connected to multiple access networks. On the other hand, in the “Multi-P” scenario the loss of buffered data in the network is avoided in the following manner (i) the LTE connection is always kept alive hence no buffered data is lost (ii) in WLAN, the flow management function at the HA sends user traffic on the WLAN link only when the user PHY mode is 9Mbps or higher. This is because when a user enters the 6Mbps mode it implies that the user is almost at the edge of coverage which is a strong indication that loss of the WLAN link is imminent. Hence, no new traffic data is sent over the WLAN link which gives the user a chance to receive the already buffered data at the access point before the loss of the link.

If a large number of packet losses are experienced or excessive packet delays are encountered during the video stream reception, the data download itself does not stop. However such conditions lead to a corrupted video stream reception at the user end which cannot be decoded and therefore its quality cannot be evaluated. In the “3GPP HO” scenario video, users experience packet losses during the handover as explained earlier and, moreover, there is also large end-to-end delay when video data is transmitted through the WLAN network. The reason is as following, when VoIP and video traffic is transmitted over LTE, it is prioritized over FTP to achieve the required QoS (i.e., throughput and delay). But, in the "3GPP HO" scenario when this traffic type is handed over to WLAN the required QoS cannot always be achieved due to the lack of QoS differentiation support by 802.11g. The "Multi-P" scenario users do not come across such problems because the flow management function can precisely estimate the network capacities and use a network path only if it can support the required data rate. Hence no congestion takes place at the base station and therefore no extreme packet delays are observed. This allows the video users to receive their streaming data without losses and delays and help them achieve higher numbers of successful or decodable video file downloads compared to the "3GPP HO" scenario.

Fig. 5 shows the average TCP throughput as experienced by the FTP and HTTP users in the downlink. The "Multi-P" algorithm achieves approximately 30% more throughput for FTP users by increasing the spectral efficiency of the networks. As for the HTTP performance, it can be seen that the two algorithms show almost similar throughput. This is because the HTTP page size is small enough to be downloaded completely during the TCP slow start phase. In this way, it cannot make full use of the available bandwidth.



(a) Average MOS value (b) Average packet delay (ms)

Fig. 6. VoIP and video service performance

Fig. 6(a) shows the average Mean Opinion Score (MOS) values of VoIP and video services as experienced by the users. MOS gives a numerical indication of the perceived quality of the media received after being transmitted and eventually compressed using codecs. MOS is expressed in one number, from 1 to 5, 1 being the worst and 5 the best. In this work, the MOS values of the wideband VoIP codec and video codec are computed using the modified E-model and Evalvid toolkit as described in [12] and [11], respectively. The "Multi-P" scenario users boast the highest achievable MOS value for individual services. On the other hand, users in the "3GPP HO" scenario suffer from a certain degradation in MOS value. Fig. 6(b) shows the end-to-end packet delay for the three service types. It can be observed that the "Multi-P" scenario once again shows its superiority over "3GPP HO" by providing shorter end-to-end packet delays.

VII. CONCLUSION

This work highlights the importance of multi-homing support in the integrated heterogeneous wireless networks of 3GPP and non-3GPP access technologies. The existing 3GPP specifications for integration of two types of the access technologies are extended following IETF standards to realize multi-homing support for the users. Following the proposed extensions, a network simulation model is developed, where 4G LTE and WLAN co-exist. This work also focuses on the problem of optimum resource utilization in such a heterogeneous network where the users and network operators can take advantage of multi-homing support. The problem of optimum network resource allocation is mathematically modeled using the linear programming technique. The proof of concept is provided through the simulation results. With help of simulation results it is shown that the proposed scheme of resource allocation brings twofold gain when compared to the 3GPP proposal. On the one hand, it significantly improves the network capacity and on the other hand it fulfills the user application QoS demands, which otherwise cannot be satisfied from QoS unaware non-3GPP access technologies.

VIII. ACKNOWLEDGMENT

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