Evaluating User-centric Multihomed Flow Management for Mobile Devices in Simulated Heterogeneous Networks

Xi Li[1]*, Olivier Mehani[2], Ramón Agüero[3], Roksana Boreli[2,4], Yasir Zaki[1], and Umar Toseef[1]

[1] University of Bremen, Bremen, Germany
{xili,yzaki,umr}@comnets.uni-bremen.de
[2] Nicta, Eveleigh, Sydney, NSW, Australia
{olivier.mehani,roksana.boreli}@nicta.com.au
[3] University of Cantabria, Santander, Spain
ramon@tlmat.unican.es
[4] University of New South Wales, Sydney, NSW, Australia

Abstract. We implemented approaches to solve the multihomed flow management problem using the OPNET simulator. We formulate a quality-aware decision method as a binary integer problem and use it (with the CPLEX solver) to drive the network selection and flow distribution in the simulated scenarios. We compare the behaviour of application flows with our approach and the most commonly implemented nowadays. This allows us to more accurately evaluate these approaches' potential when applied to real network scenarios, where adaptation loops in protocols and algorithms in the network stack may alter the expected performance. We show that, even uncalibrated, the quality-aware multihomed flow management allows to make better trade-offs between different user criteria and identify improvement directions.

1 Introduction

Accessing the Internet on the move is now the rule rather than the exception. On the one hand, new wireless network technologies provide higher capacities to cater for the increasing number of users and their needs. On the other hand, user equipments now support several of these technologies. Yet, no clear consensus exists on how to balance their use to provide "always best connected" devices [1], and the simplest method ("everything on Wi-Fi if available, or cellular otherwise") is widely implemented [2].

Most of the research work tends to focus on selecting the network(s) with the highest quality estimates. A subset of these approaches also considers using more than one interface at the same time (see Section 5), with various levels of granularity. Nonetheless, these estimated metrics are based on technical parameters of the communication. Various ITU recommendations [3], [4], [5] however

* This work was conducted while Xi Li was a visiting researcher at Nicta.

showed that the quality a user perceives (quality of experience, QoE [6]), is in no way linearly dependent on such technical metrics.

In earlier work [7], it was proposed to pay closer attention to the metrics most relevant to the user, such as the QoE, the power consumption and the access price. The generic *multihomed flow management problem* (MFM) was defined, and several approaches were tested. Results showed that directly basing optimisation decisions on user-centric metrics improved the resulting perceived quality. However, the evaluation of the results was only based on objective models applied to QoS estimates; in essence, the ideal outcome of the decision mechanism.

Here, we therefore propose to lift this shortcoming by implementing the described approach in a network simulator, in order to evaluate the behaviour of application flows when distributed to the selected networks. We implemented the main framework in OPNET and linked it to the CPLEX solver in order to implement the decision methods, and more accurately evaluate their potential. We confirm the results from [7] and show that the quality-aware multihomed flow management allows to make better trade-offs between user-visible metrics. We also identify directions to further improve these results.

The remainder of this paper is organised as follows. In the next section, we remind the reader to the multihomed flow management problem, and present our binary integer programming (BIP) formulation of the user-centric solution. In Section 3, we present the relevant performance metrics, as well as the simulation scenarios. The results of the comparison to a standard technique are presented and discussed in Section 4. We present related work in Section 5, and finally conclude and describe future work in Section 6.

2 LP Formulation of the User-centric Flow Management

The multihomed flow management problem is that of selecting the network association for each interface, distributing the flows over the active links and adjusting application parameters to the best matching set [7]. Its user-centric solution consists in maintaining a high application quality while keeping reasonable power consumption and access prices. It was expressed as a constrained optimisation problem in [7], but solving times proved to be prohibitive. We therefore reformulate it as a BIP, which were shown to be faster to solve (*e.g.*, [8]).

We want to distribute flows in set F over a set of possible links, formed by the association of a local interface i, from set I, to a remote network n, from set N. As the associations between interfaces and networks are limited to within the same technology, only a subset of $I \times N$ is actually valid. We address this limitation later. It is assumed that the capacity C_{in} and delay D_{in} of a link can be reliably obtained through the use of frameworks such as IEEE 802.21 [9], OConS [10], [11] (developed within the SAIL project [12]) or actively measured [13], [14], [15]. Additionally, the flows are assumed to have several parameter sets (*e.g.*, codecs) selectable from set C.

This creates $|F| \times |C| \times |I| \times |N|$ binary variables of the form

$$x_{fcin} = \begin{cases} 1 & \text{if flow } f \text{ with configuration } c \text{ is distributed on link } i\text{–}n \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

to optimise a given objective. Our model is defined by the following constraints

$$\begin{cases} \forall f, c, i, n, & x_{fcin} \in \{0, 1\} & \text{(binary variables)} & \text{(2a)} \\ \forall f, & \sum_{c,i,n} x_{fcin} = 1 & \text{(one parameter set per flow)} & \text{(2b)} \\ \forall i, n, & \left(\sum_{f,c} x_{fcin} C_{fc} \right) \leq C_{in} & \text{(capacity limitation).} & \text{(2c)} \end{cases}$$

It is necessary to be able to express the fact that a link is active. This is done through the use of an auxiliary variable,

$$a_{in} = \begin{cases} 1 & \text{if a link from } i \text{ to } n \text{ is active} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

with additional constraints

$$\begin{cases} \forall i, n, & a_{in} \in \{0, 1\} & \text{(binary variables)} & \text{(4a)} \\ \forall f, c, i, n & x_{fcin} \leq a_{in} & (a_{in} = 1 \text{ if any } x_{fcin} = 1) & \text{(4b)} \\ \forall i, & \sum_{n} a_{in} \leq 1 & \text{(one association per interface).} & \text{(4c)} \end{cases}$$

The goal for the user-centric flow management approach is to maximise the QoE of flows, while minimising the energy and monetary costs incurred. The general objective function is therefore

$$\max \sum_{f,c,i,n} \left(\alpha Q(f, c, C_{fc}, D_{in}) - (\beta E'_{in} + \gamma M'_{in}) C_{fc} \right) x_{fcin} - \sum_{i,n} (\beta E_{in} + \gamma M_{in}) a_{in}, \tag{5}$$

where α, β and γ are scaling and priority weights, $Q(f, c, C, D, \ldots)$ is the expected QoE as computed by objective models based on the offered QoS (as defined by ITU's E-Model [3], [4], [5], see [7] for more details), and E_{in} and M_{in} (resp. E'_{in} and M'_{in}) are the time-based and (resp. data-based) energy and monetary costs for link i–n. However, $Q(\cdot)$ is not a linear function of its arguments, and this objective cannot be used directly by the solver. To address this problem, we precompute a part of it, for each possible configuration, as utility value

$$u_{fcin} = \alpha Q(f, c, C_{fc}, D_{in}) - (\beta E'_{in} + \gamma M'_{in}) C_{fc}. \tag{6}$$

These precomputed utility values can then be used in the new linear optimisation objective,

$$\max \sum_{f,c,i,n} u_{fcin} x_{fcin} - \sum_{i,n} (\beta E_{in} + \gamma M_{in}) a_{in}. \tag{7}$$

The next section presents how this model and approach are implemented in the OPNET network simulator

3 Simulations

We implemented a basic mobility scenario with a UE moving between multiple wireless access points (WAP) under the coverage of a single LTE eNodeB using the OPNET discrete-event simulator.[2] The decision aspect is done through the use of a linear programming solver integrated within the control code of the mobility model.

3.1 OPNET Model

3GPP has specified an architecture that allows mobile users to roam between 3GPP and non-3GPP access technologies [16]. To provide users with seamless mobility, Proxy Mobile IPv6 (operator-based mobility [17]) and Dual-stack Mobile IPv6 (host-based mobility [18]) are proposed [16]. The work presented in this paper proposes an extension to the the integration of LTE and trusted non-3GPP access technology (*e.g.*, 802.11g), where the host-based mobility solution is considered. One of the issues that are not supported in the current 3GPP specification is the use of multihoming: a user can use either LTE or WLAN but not simultaneously. We therefore developed an extension which can provide users with multihoming capabilities. This is achieved by extending the implementation of MIPv6 to support multiple care-of addresses [19] and flow management functionalities [20], [21].

Fig. 1 shows an overview of the simulation network implemented in OPNET. The model is built as an extension of our previous work in LTE networks modelling [22, which include channel model details] with additional support for the integration of WLAN, extending the standard OPNET WLAN implementation to support link adaptation to user movements and changing channel conditions. Moreover, the standard OPNET MIPv6 implementation has been integrated after extending it to support multihoming and flow management. The final model includes all relevant entities that are necessary to carry out the multihoming scenario. Following [16], the home agent (HA) functions are located at the PDN gateway. The remote server in the figure acts as a correspondent node (CN). Users receive router advertisements from the eNodeB and the WLAN access points so that they can configure their care-of addresses. They then register with the HA through standard MIPv6 signalling. In this way all user traffic is tunnelled from the HA to the user, and vice-versa.

[2] http://www.opnet.com

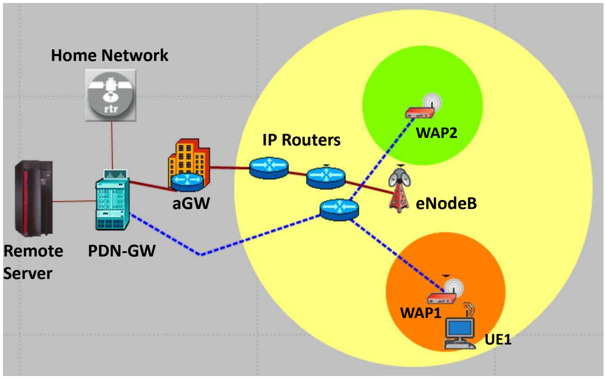


Fig. 1: OPNET simulation model. A User Equipment roams between two WAPs covered by a single LTE cell. Host-based mobility is supported within the home network through the use of MIPv6, with the MCoA extensions.

3.2 CPLEX Integration

CPLEX[3] provides a large set of APIs for various languages. We used the CPLEX Callable C Library for the integration with OPNET. After adding this library in the OPNET repository, the available CPLEX functions can be called directly from OPNET.In this work, we need to solve a BIP to decide the flow and network associations (see Section 2). We used CPLEX's MIP optimiser to compute the solutions to our MFM problem.

This allowed us to implement a practical online decision method in the user device. With this method, the proposed decision function can be called at any time, and the decision results obtained from the solver directly. They are then used to enforce the network selection and flow distribution in the simulated environment. Currently, a periodic triggering method calls the solver at regular intervals. The periodicity should be chosen properly; if too large, this may lead to performance degradation due to late adaptation, but too small a value will cause changes to happen too frequently, creating higher overheads for the network managements. Finding an optimised setting of this interval, or using a more dynamic triggering algorithm (*e.g.*, based on new arrivals or departures of flows), is left for future work.

To support correct decision-making, we rely on having proper estimates of all access network conditions such as their availability, the link capacity (C_{in}) and delays (D_{in}). The network capacity depends on the user's distance from the base stations and is thus estimated inside the mobility model.

The WLAN link capacity is estimated based on the selected PHY model, depending on the distance to the WAP. Similarly, we estimate the available capacity of the LTE network based on the measured average SINR and the

[3] http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/

amount of available radio resources (*i.e.*, number of physical resource blocks). A more accurate estimation of per-user link capacity for multi-user scenarios, by considering resource scheduling at the WAPs and eNodeBs, is left for future work. Given the link capacity per network, we are able to estimate the probable per-flow capacities (C_{fc}), in order to derive potential utility values. For elastic traffic (*e.g.*, TCP-based traffic), it is assumed that each flow will get an equal share. We therefore calculate the flow capacities by dividing the link capacity C_{in} by the total number of active elastic flows of the user. However, for real time traffic, the flow capacity C_{fc} depends on the application codec rate. The link delays are estimated based on the measured RTTs. With the estimated flow capacity, link capacities and delays, the per-flow QoE can be estimated following ITU's objective models. Alongside the data-based energy and monetary costs, this allows to evaluate the utilities following (6). These pre-computed utilities and resultant objective function (7) are then expressed in a form suitable for CPLEX's MIP solver.

3.3 Performance Metrics

Several metrics are relevant to our study. First, we implemented the ITU QoE objective models, following our description in [7], to be computed based on actual network conditions experienced by the flows, such as flow throughput or packet delay, reported from the simulator. The two other important user metrics are the power consumption, and the monetary price.

We use simple models for these costs, where some comes from having an interface up and connected to a network, and some comes from transferring data over the thus created link. For each run, we can therefore determine how much battery has been used, and how much the network usage has cost. Table 1.1 shows the base values we have chosen for this paper, based on power data from [23], and arbitrary estimates for access costs ($5 for 500 MB is reasonably common). All are expressed per time unit as the solver is called at a periodic interval. It is however important to note that these parameters are not hardcoded, and that other values are possible.

Delays are an important factor in the quality perception, and is indeed already taken into account for voice [3] and web traffic [4]. Yet, it is interesting to consider it separately as it also gives an indication of the load along the end-to-end path, with higher load creating fuller buffers and queues, and larger packet

Table 1.1: Battery and monetary costs used in the scenarios.

Technology	**Power**		**Price**	
	E **[%/s]**	E' **[(%/B)/s]**	M **[$/s]**	M' **[($/B)/s]**
Cellular	6.5×10^{-3}	2.3×10^{-13}	0	1×10^{-8}
WLAN	3.6×10^{-3}	9.9×10^{-14}	0	0

delays. As it also gives an indication of the load along the end-to-end path, it is however interesting to consider it separately too.

3.4 Comparison Approach

In this paper, we are mostly interested in presenting and validating our simulation model to confirm its proper behaviour. Rather than comparing the proposed approach to many techniques, we selected the most common one, where a mobile device senses the networks around it, and favours any WLAN and uses the cellular link as a last resort [2], which we call 3GPP-HO [24]. In essence, this means that the mobile device will always be connected to the LTE network, but switch to the WLAN link shortly after it becomes available, and keeps using it until it becomes virtually unreachable.

3.5 Simulation Scenarios

We chose to study two different scenarios to evaluate our proposed quality-aware approach for different application types and compare it to the 3GPP-HO approach.

Real-time video four different codec rates (400 kbps, 600 kbps, 800 kbps and 1000 kbps); fixed frame rate of 30 fps;
Elastic Web traffic 1 MB web objects; inter-arrival time of 100 s.

In both scenarios, the user stays within the coverage of a single LTE eNodeB as shown in Fig. 1. However, in the first scenario the user is moving from WAP1 to WAP2, experience vertical handovers between cellular network and WLAN. In the second scenario, the user is only moving with WAP1 and can always connect to either or both WLAN and LTE networks.

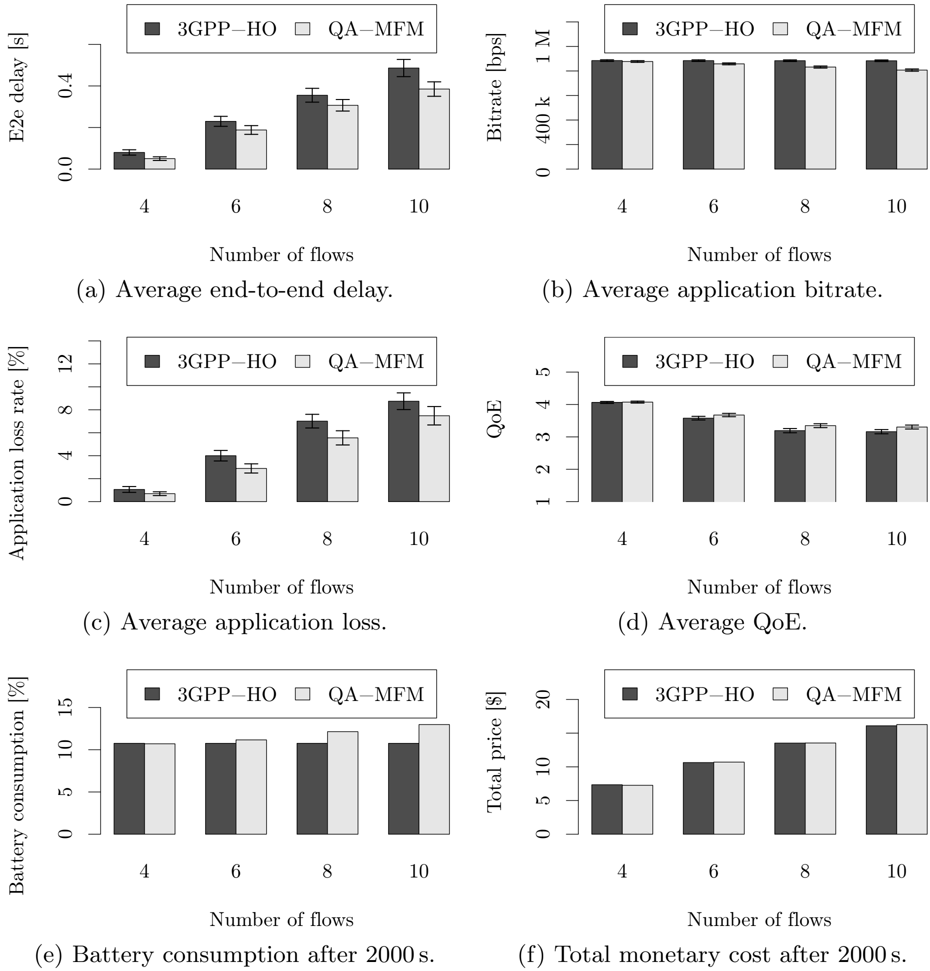
For the quality-aware multihomed flow management approach, the time interval of triggering the decision function is set to 1 s. To calculate the utility and objective function, the scaling and priority weights for the QoE, energy and cost are all set to 1 (calibrating these values is left for future work). The battery and monetary costs per network are defined in Table 1.1.

4 Results and Discussion

This section presents the results for both the real-time and elastic scenarios, then some timing information about the solver is given.

4.1 Real-time Video Traffic

We recall that our proposed quality-aware multihomed flow management (QA-MFM) adjusts the bitrate of the video flows to match the available capacities. Fig. 2 compares our approach to the 3GPP-HO approach with respect to the



(a) Average end-to-end delay. (b) Average application bitrate.

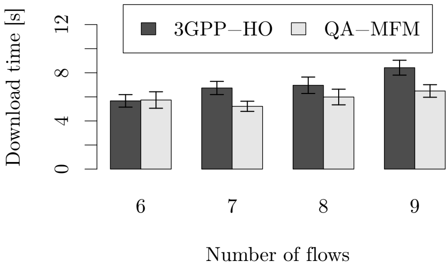
(c) Average application loss. (d) Average QoE.

(e) Battery consumption after 2000 s. (f) Total monetary cost after 2000 s.

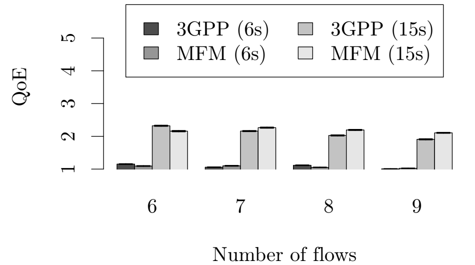
Fig. 2: Metrics for the real-time video scenario for a varying number of flows. Error bars are placed at $1.96SE$ as an estimate of the 95% CI for the mean.

selected metrics. In essence, the QA-MFM achieves a lower delay, slightly lower bitrate, lower application loss-rate and slightly better QoE at the cost of a higher battery consumption and very slightly higher cost for one-way real-time video traffic.

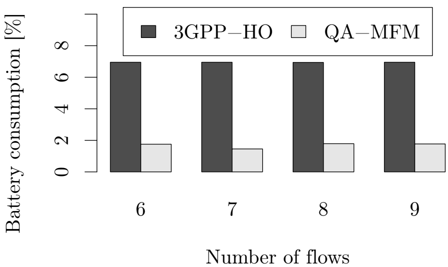
The results for the QoE, battery consumption and price are coherent with the predictions of [7]. However, the difference in quality of experience (Fig. 2d) is much smaller than expected. We hypothesise it is due to the packetisation of application data units tending to fragment one video frame into several UDP packets. Losing only one of many packets therefore results in the loss of the entire video frame; for a packet loss rate of p, this means that the application-layer loss



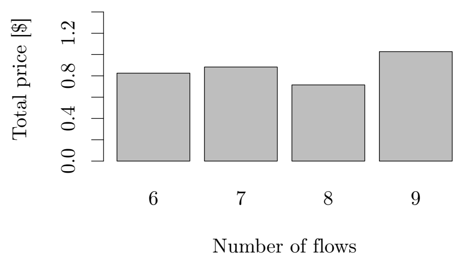
(a) Average download time.



(b) Average QoE for two different user expectations (6 and 15 s).



(c) Battery consumption after 2000 s.



(d) Total monetary cost after 2000 s (3GPP-HO is always 0 in this scenario).

Fig. 3: Performance for the elastic web traffic scenarios.

rate would be $(1-p)^n$, where n is the number of UDP packets a video frame is fragmented in. In addition, we did not take header overhead into account. This has led to overestimating the available capacity, even with the QA-MFM approach. This explains the application losses shown in Fig. 2c.

An interesting effect of our proposed approach is that, reducing the bitrate of the video flows to match the networks' capacities, it creates less congestion at the intermediate routers, which in turns allows to reduce the packet delay, as shown in Fig. 2a. We believe that addressing the capacity estimation problems mentioned previously would also allow to further reduce these delays.

4.2 Elastic Web Traffic

The comparison results for the web traffic scenario are shown in Fig. 3. At a higher price, the QA-MFM delivers shorter download times and lower battery usage. Even though our approach tends to achieve a higher quality than the 3GPP-HO, the QoE is lower than expected. We believe it could be further improved with a proper calibration of the optimisation weights, which we keep as future work.

We recall from Section 3.5 that, in this scenario, the UE remains within range of both the LTE network, and one wireless access point. It is therefore expected that, in order to improve the performance, the QA-MFM would use the LTE network in addition to the WLAN network that the 3GPP-HO would always choose. This therefore explains that our approach costs some money, also using the cellular network in this case (Fig. 3d). Another key advantage of the QA-MFM approach is to save the battery by switching off the interfaces in case there is no data transfer required by the user, given the ON-OFF behaviour of the web traffic, while the interfaces were always on with the 3GPP-HO approach, the QA-MFM simply deactivated them. The QA-MFM approach therefore consumed much less battery than the 3GPP-HO (Fig. 3c).

While the download time is shortened by the quality-aware approach (Fig. 3a), the QoE is not very much improved (almost at its worst in the 6 s cases). Fig. 3b shows two estimates of this QoE, depending on the expectation of the user with respect to the session duration. In this scenario, we only transferred 1 MB objects, for which the expectations of 6 and 15 s may have been a bit too great. Internally, the decision mechanism only used a 6 s-based estimation, regardless of the transfer size. This highlights a problem in calculating the QoE for elastic traffic based on [4] for the QA-MFM approach, as it becomes necessary to estimate what the expectations of the user would be in order to make the proper decision. It is the subject of future work to address this question.

4.3 Solving Time

The solving time is the time needed by the CPLEX LP solver for one iteration of calculation of the decisions on network selections, flow distributions and choosing proper application parameter per application flow. The problem size is determined by the number of constraints and variables, which increase with the number of active flows, the number of networks, and configurable flow parameters. As the QA-MFM problem is to be solved per user, the time to solve the BIP does not dependent on the number of users in the network. The average solving time for all our presented scenarios are shown in figure 4. It exhibits a sub-linear trend with an increasing number of constraints and variables. For our largest scenario (9 web flows), the mean solving time lies within $(186, 296)$ ms with 95% confidence.

As mentioned in Section 3.5, we used a periodic trigger to call the linear solver every second. With a grand maximum of 0.39 s, this means that this optimisation-based technique is well-suited and feasible for making real-time decisions in real systems.[4]

[4] Simulations for this work were run on 2.67 GHz Xeon X5550 machines. However, with the increasing CPU power of mobile devices, it seems reasonable that our approach can scale.

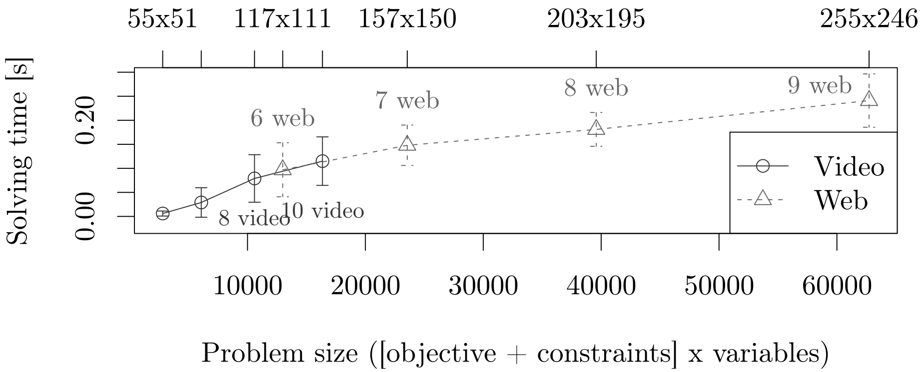


Fig. 4: Average solving time depending on the problem size (10 random samples). Error bars show a 95% CI for the mean. Labels indicate the scenario.

5 Related Work

This section reviews work related to metrics used for network selection as well as various decision techniques. A more detailed version of this review can be found in [25, chap. 2, sec. 2.3].

5.1 Criteria for Network Selection

A large range of criteria has been proposed to discriminate access links and networks in order to select the best ones to connect to. The simplest mechanisms are based on measuring the quality of the radio signal (*e.g.*, signal-to-noise ratio or received signal strength) and comparing it to a threshold [26]. The same thresholding approach can be applied to more precise metrics from the access link such as the delay or data rate [27], [28], [29], [30].

More relevant than the link layer properties for communication facilitated by transport protocols like TCP, end-to-end parameters such as network path capacities or RTTs are important to support feature-rich applications [27], [28], [30], [31], [32], [33], [34], [35], [36], [37]; some proposals also specifically take the application requirements into account in this phase [29], [38]. Additionally, some networks only provide limited connectivity to the rest of the infrastructure or require specific credentials to grant access; the reachability of the Internet [33] has also been proposed as a criteria in this case.

As we argue in this paper, battery life is important in a mobile context, and trade-offs have been considered to preserve it [23], [34], [35], [36]. Similarly, multiple approaches take monetary considerations into account [29], [31], [32], [35], [36], [39]. The currently observed application layer performance, as observed by already connected nodes, can also be used as an indication of the "health" of a network link [39]. However, QoE is still very rarely used for such tasks.

5.2 Flow Distribution

The distribution of application flows over multiple uplinks active at the same time could be seen as a superset of the network selection schemes just presented. However, the flow scheduling problem has to accommodate additional constraints such as that only the networks to which the device is associated can be used, some of which are mutually exclusive. Two main classes of solutions can be distinguished.

The first group applies traffic classification and load balancing approaches of conventional wired technologies after network uplinks have been selected and established. Simple policies, based on flows' destinations or port, to decide which network is the most appropriate are often seen [40]. However, more complex techniques proposed distribute new flows with more elaborate heuristics (*e.g.*, random or load balancing) [30], [41].

Approaches in the second class take a more holistic approach by performing network selection and flow distribution at the same time. A number of solutions rely on knowledge of the applications' requirements to select the network which most closely matches them [31], [35]. These approaches however come at the cost of a larger solution space to search. To address this issue, the problem was modelled as a Markov chain [42] to leverage decision process techniques of that field. Binary integer programming techniques have also been proposed [36].

5.3 Multi-criteria Selection Techniques

To enable a finer selection of an access network, it may also be argued that considering a single criterion is not sufficient. Therefore, a number of more recent proposals use some sort of multi-objective optimisation technique where the various criteria can be composed and compared.

Common approaches use utility functions in order to create a weighted compound variable for each network, to be compared to a threshold or that of other networks [38], [43]. The analytic hierarchy process (AHP) [44], a more formal way of ranking choices according to multiple criteria, is also proposed to find the highest ranked options [27], [45].

A number of proposals introduce sub-optimal but computationally efficient algorithms [32], [34]. Linear programming techniques have been proposed to find optimal solutions for specific formulations of the problems [8], [36].

Finally, weights or scaling factors are an important parameter in multi-objective optimisations, as the input variables need be mapped to comparable ranges. Genetic algorithms [29] or the grey relational analysis [27], [46] can be used to derive these weights. This preprocessing is also often done using fuzzy logic approaches [28], [29], [45].

6 Conclusion and Future Work

In this paper, we presented our integration of a linear programming solver with a discrete-event network simulator. This allows us to drive the multihomed flow management by optimising user-level metrics such as the quality of experience, battery life or access price. We also presented comparison results, using this system, that show that the QA-MFM performs better than the legacy techniques of only choosing one best network, however slightly.

It is important to note that the version of the QA-MFM we evaluated here was not calibrated. It is the subject of future work, enabled by the system presented in this paper, to investigate questions about the QA-MFM approach such as properly setting the weights of the objective function—or exploring other forms for this function altogether—the implementation of more cross-layer signals to inform the transport protocols to the decision, or other optimisation triggering approaches, amongst others. This model will also enable simulations in more realistic scenarios and, more specifically, with a higher number of users, to evaluate the load this approach creates on the visited networks.

Acknowledgements

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References

[1] E. Gustafsson and A. Jonsson. "Always Best Connected". In: *IEEE Wireless Communications* 10.1 (2003).

[2] M. Wasserman and P. Seite. *Current Practices for Multiple-Interface Hosts*. RFC 6419. 2011.

[3] *The E-Model, a Computational Model for Use in Transmission Planning.* Recommendation G.107. 2005.

[4] *Estimating End-to-End Performance in IP Networks for Data Applications*. Recommendation G.1030. 2006.

[5] *Opinion Model for Video-Telephony Applications*. Recommendation G.1070. 2007.

[6] K. Kilkki. "Quality of Experience in Communications Ecosystem". In: *Journal of Universal Computer Science* 14.5 (2008).

[7] O. Mehani, R. Boreli, M. Maher, and T. Ernst. "User- and Application-Centric Multihomed Flow Management". In: *LCN 2011*. 2011.

[8] J. Choque, R. Agüero, E.-M. Hortigüela, and L. Muñoz. "Optimum Selection of Access Networks Within Heterogeneous Wireless Environments Based on Linear Programming Techniques". In: *MONAMI 2010*. 2010.

[9] E. Piri and K. Pentikousis. "IEEE 802.21". In: *The Internet Protocol Journal* 12.2 (2009).

[10] R. Agüero et al. "OConS: Towards Open Connectivity Services in the Future Internet". In: *MONAMI 2011*. 2011.

[11] L. Diez, O. Mehani, L. Suciu, and R. Agüero. “Design and Implementation of the Open Connectivity Services Framework”. In: *MONAMI 2012*. 2012.
[12] SAIL project. *Architectural Concepts of Connectivity Services*. Deliverable FP7-ICT-2009-5-257448-SAIL/D-4.1(D-C.1). 2011.
[13] S. Shalunov et al. *A One-way Active Measurement Protocol (OWAMP)*. Tech. rep. 4656. 2006.
[14] K. Hedayat et al. *A Two-Way Active Measurement Protocol (TWAMP)*. RFC 5357. 2008.
[15] B. Constantine, G. Forget, R. Geib, and R. Schrage. *Framework for TCP Throughput Testing*. RFC 6349. 2011.
[16] *Architecture Enhancements for Non-3GPP Accesses*. TS 23.402. 2012.
[17] *Proxy Mobile IPv6 (PMIPv6) Based Mobility and Tunnelling Protocols; Stage 3*. TS 29.275. 2010.
[18] D. Johnson, C. E. Perkins, and J. Arkko. *Mobility Support in IPv6*. RFC 3775. 2004.
[19] R. Wakikawa et al. *Multiple Care-of Addresses Registration*. RFC 5648. 2009.
[20] G. Tsirtsis, G. Giaretta, H. Soliman, and N. Montavont. *Traffic Selectors for Flow Bindings*. RFC 6088. 2011.
[21] G. Tsirtsis et al. *Flow Bindings in Mobile IPv6 and Network Mobility (NEMO) Basic Support*. RFC 6089. 2011.
[22] Y. Zaki, T. Weerawardane, C. Görg, and A. Timm-Giel. “Long Term Evolution (LTE) Model Development Within OPNET Simulation Environment”. In: *OPNETWORK 2011*. 2011.
[23] H. Petander. “Energy-aware Network Selection Using Traffic Estimation”. In: *MICNET 2009*. 2009.
[24] U. Toseef, Y. Zaki, A. Timm-Giel, and C. Görg. “Uplink QoS Aware Multihoming in Integrated 3GPP and non-3GPP Future Networks”. In: *MONAMI 2012*. 2012.
[25] O. Mehani. “Contributions to Mechanisms for Adaptive Use of Mobile Network Resources”. PhD thesis. 2011.
[26] S. Mohanty and I. F. Akyildiz. “A Cross-Layer (Layer 2 + 3) Handoff Management Protocol for Next-Generation Wireless Systems”. In: *IEEE Transactions on Mobile Computing* 5.10 (2006).
[27] Q. Song and A. Jamalipour. “Network Selection in an Integrated Wireless LAN and UMTS Environment Using Mathematical Modeling and Computing Techniques”. In: *IEEE Wireless Communications* 12.3 (2005).
[28] A. L. Wilson, A. Lenaghan, and R. Malyan. “Optimising Wireless Access Network Selection to Maintain QoS in Heterogeneous Wireless Environments”. In: *WPMC 2005*. 2005.
[29] M. Alkhawlani and A. Ayesh. “Access Network Selection Based on Fuzzy Logic and Genetic Algorithms”. In: *Advances in Artificial Intelligence* 2008 (2008).

[30] S. Kandula, K. C. Lin, T. Badirkhanli, and D. Katabi. "FatVAP: Aggregating AP Backhaul Capacity to Maximize Throughput". In: *NSDI 2008*. 2008.

[31] V. Gazis, N. Alonistioti, and L. Merakos. "Toward a Generic "Always Best Connected" Capability in Integrated WLAN/UMTS Cellular Mobile Networks (and Beyond)". In: *IEEE Wireless Communications* 12.3 (2005).

[32] E. Adamopoulou, K. Demestichas, A. Koutsorodi, and M. Theologou. "Intelligent Access Network Selection in Heterogeneous Networks - Simulation Results". In: *ISWCS 2005*. 2005.

[33] A. J. Nicholson et al. "Improved Access Point Selection". In: *MobiSys 2006*. 2006.

[34] B. Xing and N. Venkatasubramanian. "Multi-constraint Dynamic Access Selection in Always Best Connected Networks". In: *MobiQuitous 2005*. 2005.

[35] J.-M. Bonnin. "La diversité technologique au service des terminaux et routeurs multiconnectés". Mémoire d'habilitation à diriger des recherches. 2008.

[36] V. E. Zafeiris and E. A. Giakoumakis. "Mobile Agents for Flow Scheduling Support in Multihomed Mobile Hosts". In: *IWCMC 2008*. 2008.

[37] J. Pang et al. "Wifi-Reports: Improving Wireless Network Selection with Collaboration". In: *MobiSys 2009*. 2009.

[38] X. Liu, V. O. K. Li, and P. Zhang. "Joint Radio Resource Management through Vertical Handoffs in 4G Networks". In: *GlobeCom 2006*. 2006.

[39] K. Piamrat, C. Viho, A. Ksentini, and J.-M. Bonnin. *QoE-aware Network Selection in Wireless Heterogeneous Networks*. Tech. rep. RR-7282. 2010.

[40] M. Tsukada, O. Mehani, and T. Ernst. "Simultaneous Usage of NEMO and MANET for Vehicular Communication". In: *TridentCom 2008*. 2008.

[41] A. J. Nicholson, S. Wolchok, and B. D. Noble. "Juggler: Virtual Networks for Fun and Profit". In: *IEEE Transactions on Mobile Computing* 9.1 (2010).

[42] J. Singh, T. Alpcan, P. Agrawal, and V. Sharma. "A Markov Decision Process Based Flow Assignment Framework for Heterogeneous Network Access". In: *Wireless Networks* 16.2 (2010).

[43] S. Aust, C. Görg, and C. Pampu. *Policy Based Mobile IPv6 Handover Decision (POLIMAND)*. Internet-Draft draft-iponair-dna-polimand-02.txt. 2005.

[44] T. L. Saaty. *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*. Vol. 6. 2000.

[45] P. M. L. Chan et al. "Mobility Management Incorporating Fuzzy Logic for Heterogeneous a IP Environment". In: *IEEE Communications Magazine* 39.12 (2001).

[46] S. Liu et al. "Introduction to Grey Systems Theory". In: *Grey Systems—Theory and Applications*. Vol. 68. 2011. Chap. 1.