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

Xi Li[1], Olivier Mehani[2]
Ramon Aguero[3], Roksana Boreli[2], Yasir Zaki[1], Umar Toseef[1]

[1] ComNets, University of Bremen
[2] Nicta, Sydney NSW, Australia
[3] University of Cantabria, Santander, Spain

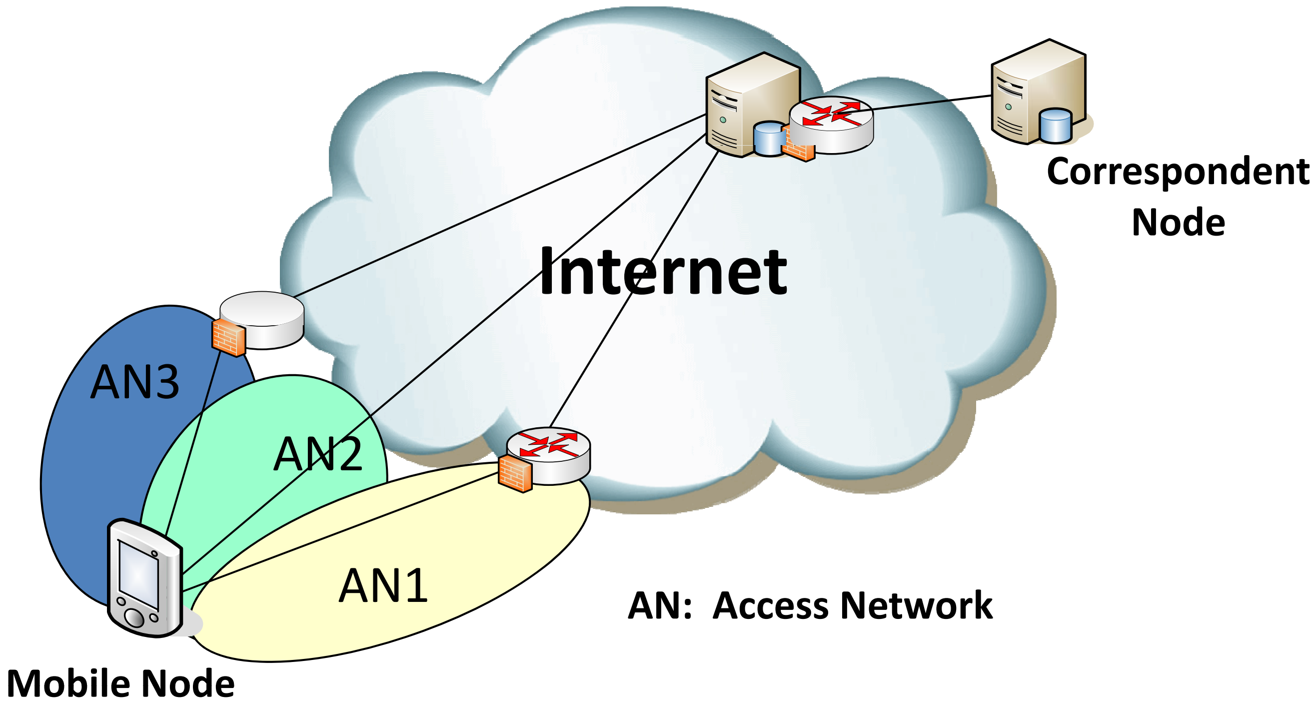
This work was conducted during my visit at Nicta

Outline

- Motivation and Related Work
- User-Centric Flow Management
- Simulation Model and Results
- Conclusion and Outlook

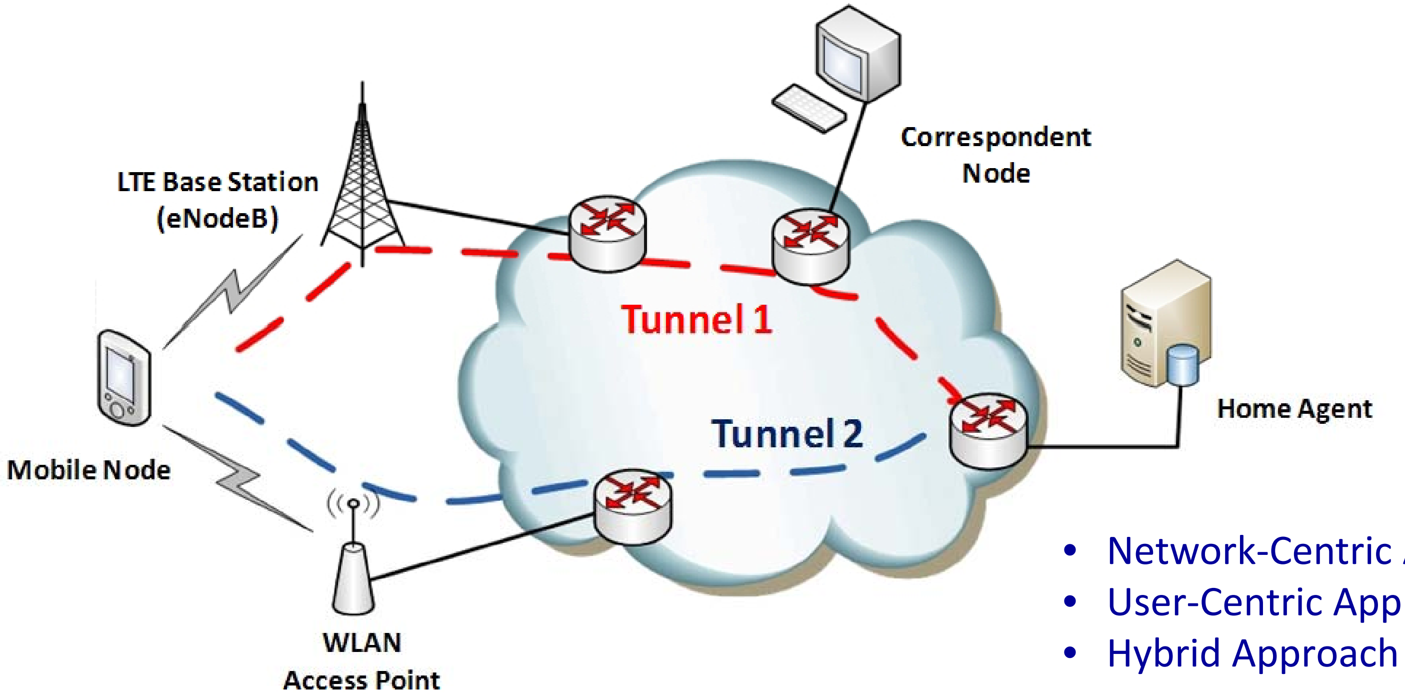
Motivation

- More wireless access networks of various types are being deployed widely with overlapping coverage areas – heterogeneous wireless network environment
- More end user devices (e.g. mobile phones, IPADs) are equipped with multiple interfaces to connect to more than one radio access (e.g. WiFi, UMTS/HSPA, LTE)
- How to select and use the most appropriate networks (one or more than one) to provide "Always Best Connected" - Need for proper flow management for a multihomed mobile device



Multihomed Flow Management

- Network Selection
  - Select the best/most suitable access networks (one or more than one) to provide "Always Best Connected"
- Flow Distribution
  - Distribution of application flows over the selected networks, for all the applications running on the mobile device



- Network-Centric Approach
- User-Centric Approach
- Hybrid Approach

Related Work

- Most of the research work tends to focus on selecting the networks with the highest Quality of Service (QoS) estimates, while Quality of Experience (QoE) is still very rarely used for such tasks.

- NICTA has proposed a user- and application-centric Multihomed Flow Management (MFM) in previous work [1]*, which pays closer attention to the metrics most relevant to the user (perceived quality, battery consumption and cost).
  - The MFM problem was expressed as a constrained optimisation problem (with MiniZinc), but solving times proved to be prohibitive.
  - The evaluation of the results was only based on the QoS estimates and thus only gave the ideal outcome of the decision mechanism.

[1]* Olivier Mehani, Roksana Boreli, Michael Maher, and Thierry Ernst. "User- and Application Centric Multihomed Flow Management". Published in LCN 2011.

- In this work, we propose to lift the above shortcomings by
  - Reformulating the MFM problem as a binary integer program (using CPLEX solver [7]) to reduce the solving time.
  - Implementing the proposed MFM approach in the OPNET simulator developed by UHB [8], in order to more accurately evaluate the behavior of application flows when distributed to the selected networks.

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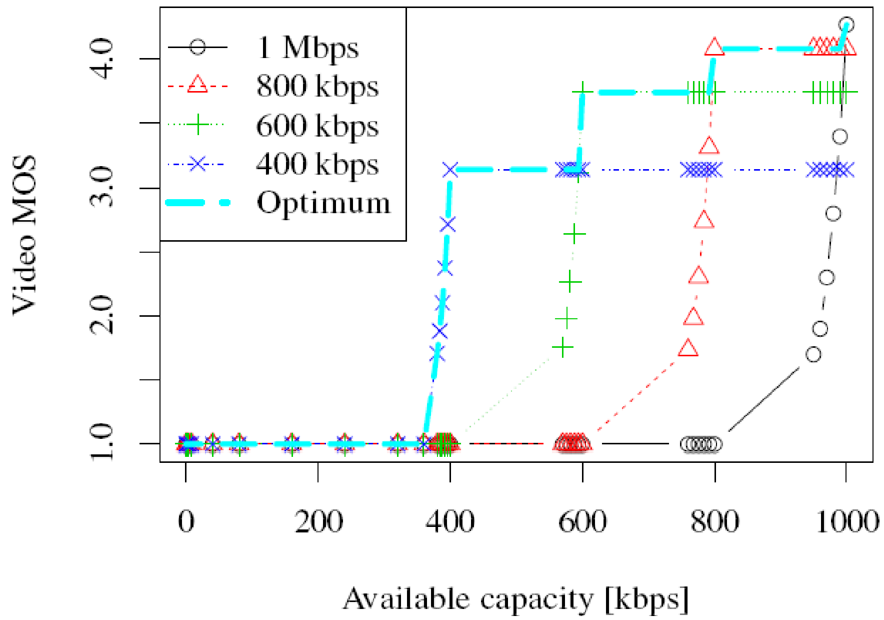
User-Centric Quality-aware Multihomed Flow Management (QA-MFM)

Main Ideas:

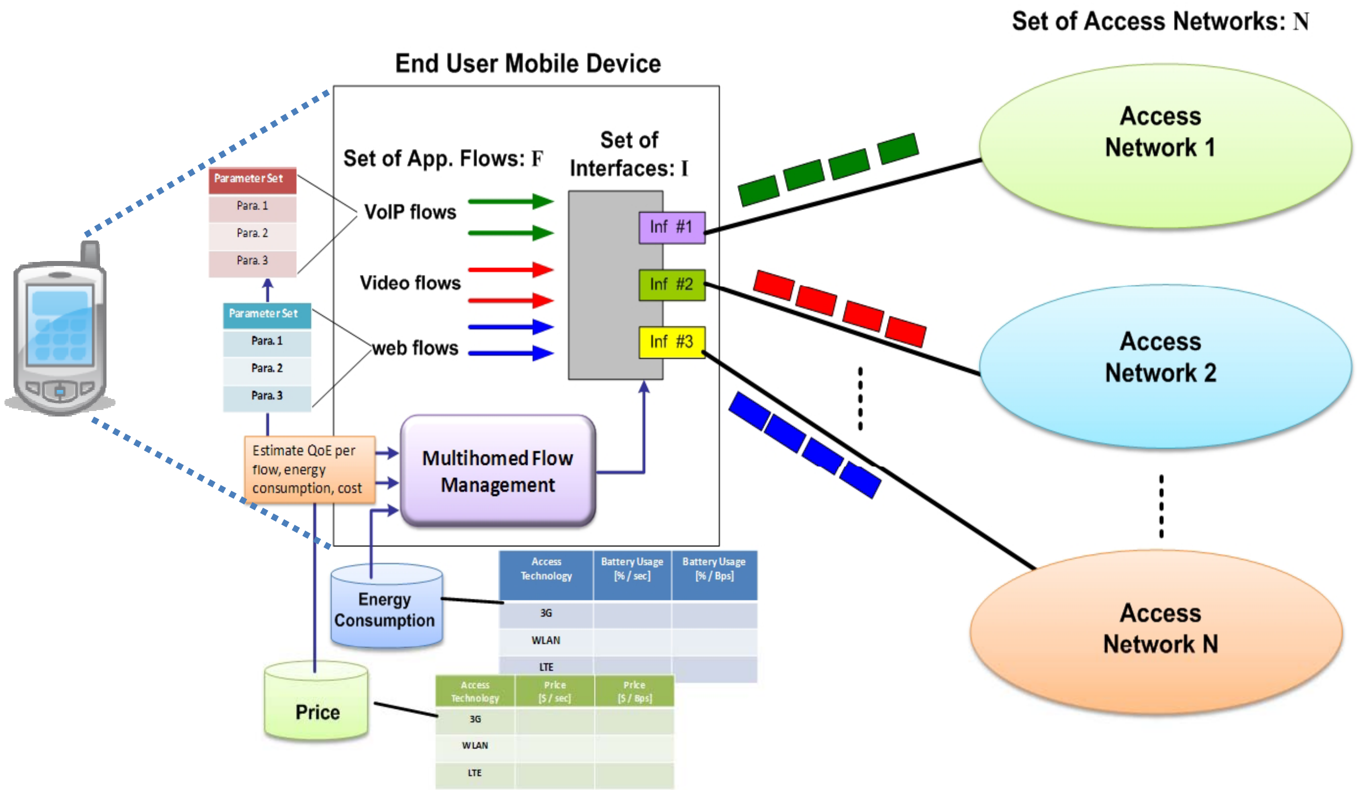
- The proposed approach combines
  - Network selection
  - Flow distribution
  - Application flow awareness (adaptive variation of application/protocol parameters)
- Considers three user-centric criteria
  - Application quality (QoE)
  - Mobile resource use (power)
  - Price of network service
- Directly considers the application QoE rather than relying on the network QoS



Source: Olivier Mehani, Roksana Boreli, Michael Maher, and Thierry Ernst. "User- and Application Centric Multihomed Flow Management". Published in LCN 2011.

QoS-based decisions may not lead to the best user-perceived performance, due to non-linear relationship between the applications quality QoE and QoS

User-Centric Quality-aware Multihomed Flow Management (QA-MFM)



Given

- Set of Application Flows: **F**
- Set of networks: **N**
- Set of Interfaces: **I**
- Set of application parameter: **C**

Estimate

- QoE based on network QoS
- Power consumption
- Network costs

We need to decide

- Network / Interface association
- Select the most appropriate access network for each flow
- Select best suitable application parameter for each flow

Triple Objectives:

Maintaining a high performance quality (**maximize the QoE**) while keeping low power consumption (**minimize the power usage**) and low access prices (**minimize the network cost**)

Linear Programming (LP) Formulation

Notations

$\boldsymbol{N}$	Set of networks: network $n \in N$
$\boldsymbol{I}$	Set of Interfaces: interface $i \in I$
$\boldsymbol{F}$	Set of application flows : flow $f \in F$
$\boldsymbol{C}$	Set of application flow parameter sets (e.g. codecs) : $c \in C$
C_{in}	The capacity of a link
D_{in}	The delay of a link
E_{in}	Time-based energy consumption [% / sec]
E_{in}'	data-based energy consumption [% / Bps]
M_{in}	Time-based monetary cost [$ / sec]
M_{in}'	data-based monetary cost [$ / Bps]
Q	estimated QoE of the flow: Q (f, c, C_{in}, D_{in})

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

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

LP Formulation of the User-centric Flow Management

Objective Function

- maximize the QoE of flows
- minimize the energy (battery consumption)
- minimize the monetary cost

maximize QoE

Minimize (data-based) power and costs

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

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

Minimize (time-based) power and cost

α, β *and* γ are scaling and priorty weights of the QoE, energy, and cost

LP Formulation of the User-centric Flow Management

- However Q (•) is not a linear function of its arguments. To address this problem, we pre-compute the utility

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

maximize QoE

Minimize (data-based) power and costs

Matrix $|F| \times |C| \times |I| \times |N|$

f	(i, n)	c	C_{in} D_{in}	Q (1-5)	$C_{fc} \cdot E_{in}'$	$C_{fc} \cdot M_{in}'$
	⋮		⋮ ⋮			

- Then the above calculated utility values are used in the linear optimisation objective

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

Minimize (time-based) power and cost

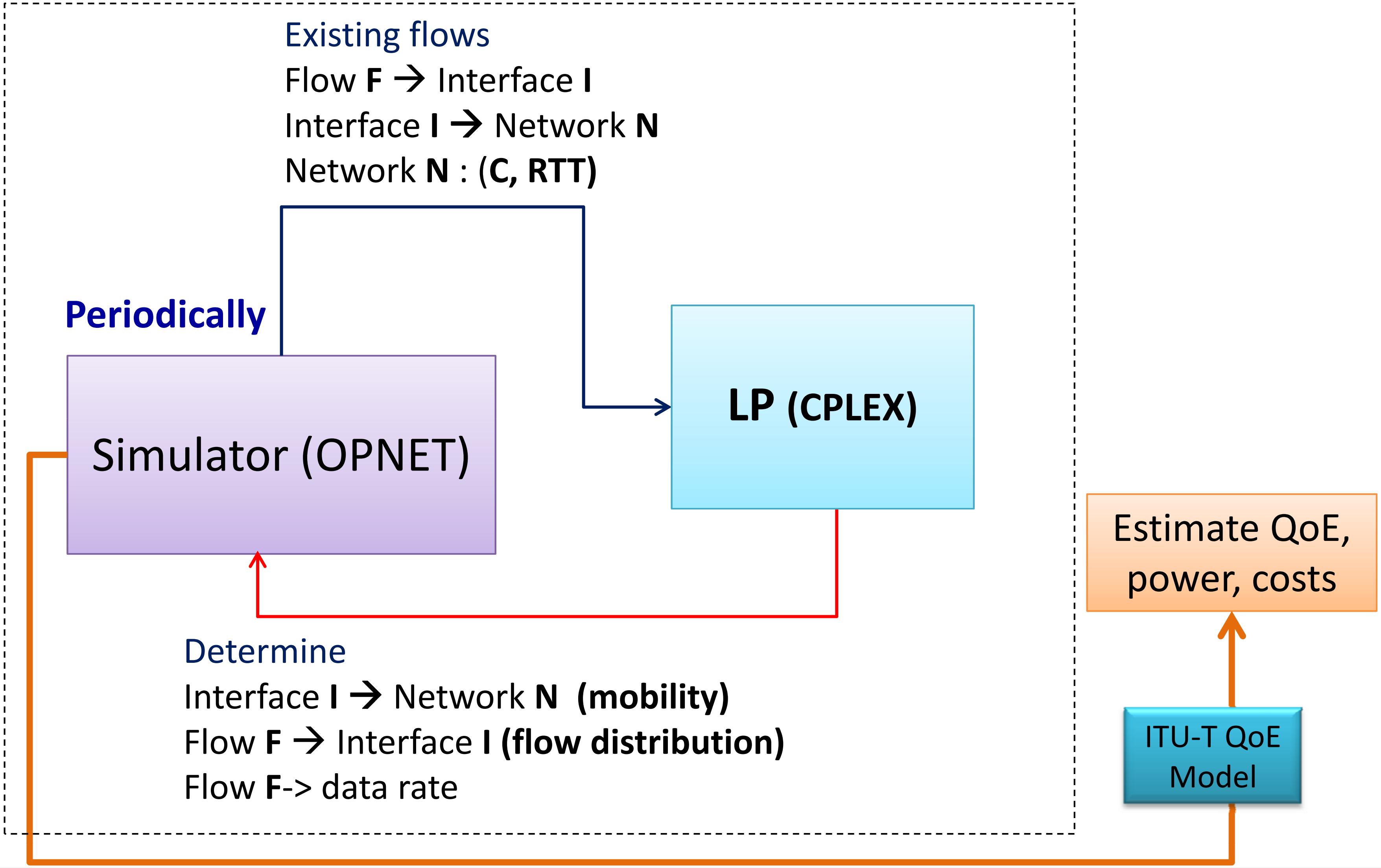
Defined Constraints

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

with additional constraints

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

Implementation in the Simulation



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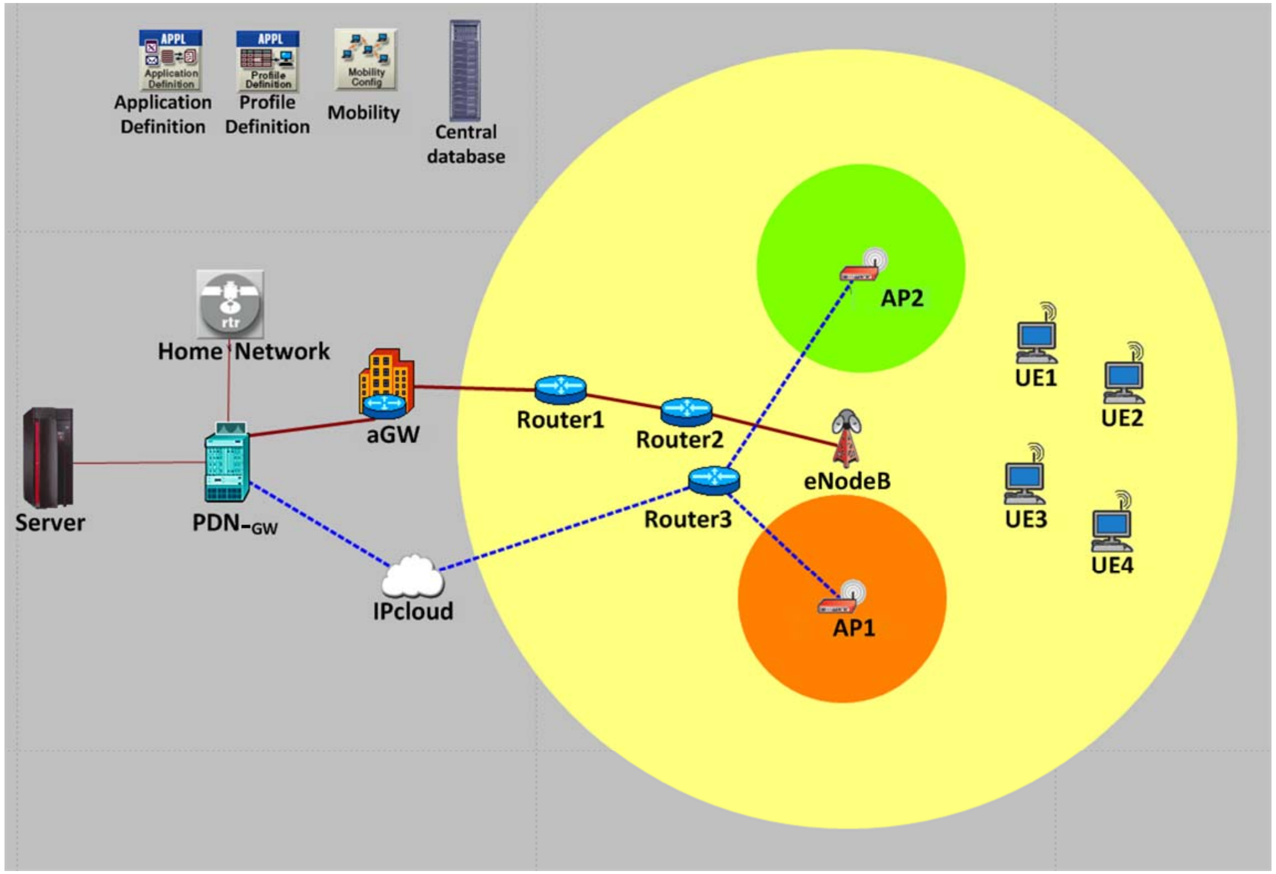
Simulation Model for 3GPP LTE Interconnected with WLAN

- ComNets Bremen developed an OPNET Simulation Model for 3GPP LTE Interconnected with WLAN and used it for SAIL project



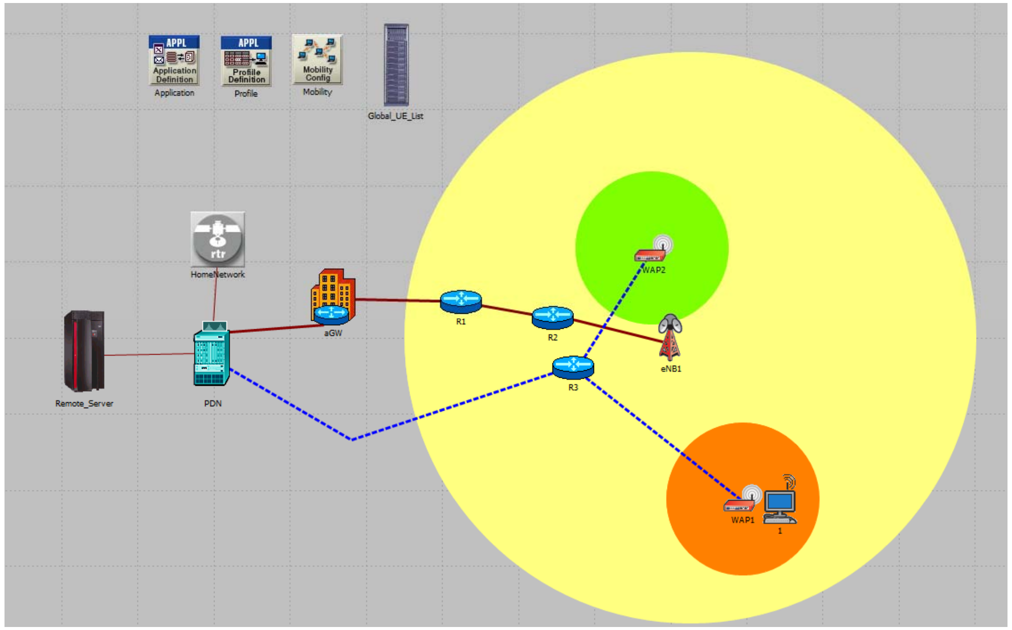
2 Flow Management Approaches:

- 3GPP-HO (most common approach):
  Select WIFI if available, or cellular otherwise
- QA-MFM:
  Proposed user centric quality-aware MFM approach

Image source: *L. Zhao, Y. N. Zaki, A. Udugama, U. Toseef, A. Timm-Giel and C. Görg, "Open Connectivity Services for Future Networks", presented in CEWIT 2011, New York, USA, Nov. 2-3, 2011*

Simulation Scenario

- 1 user moves within the coverage of a single LTE cell



Study two scenarios

- <u>Real-time Video</u>
  - 4 different codec rates (400kbps, 600kbps, 800kbps, 1000kbps), fix frame rate of 30 fps
  - User is moving from WAP1 to WAP2

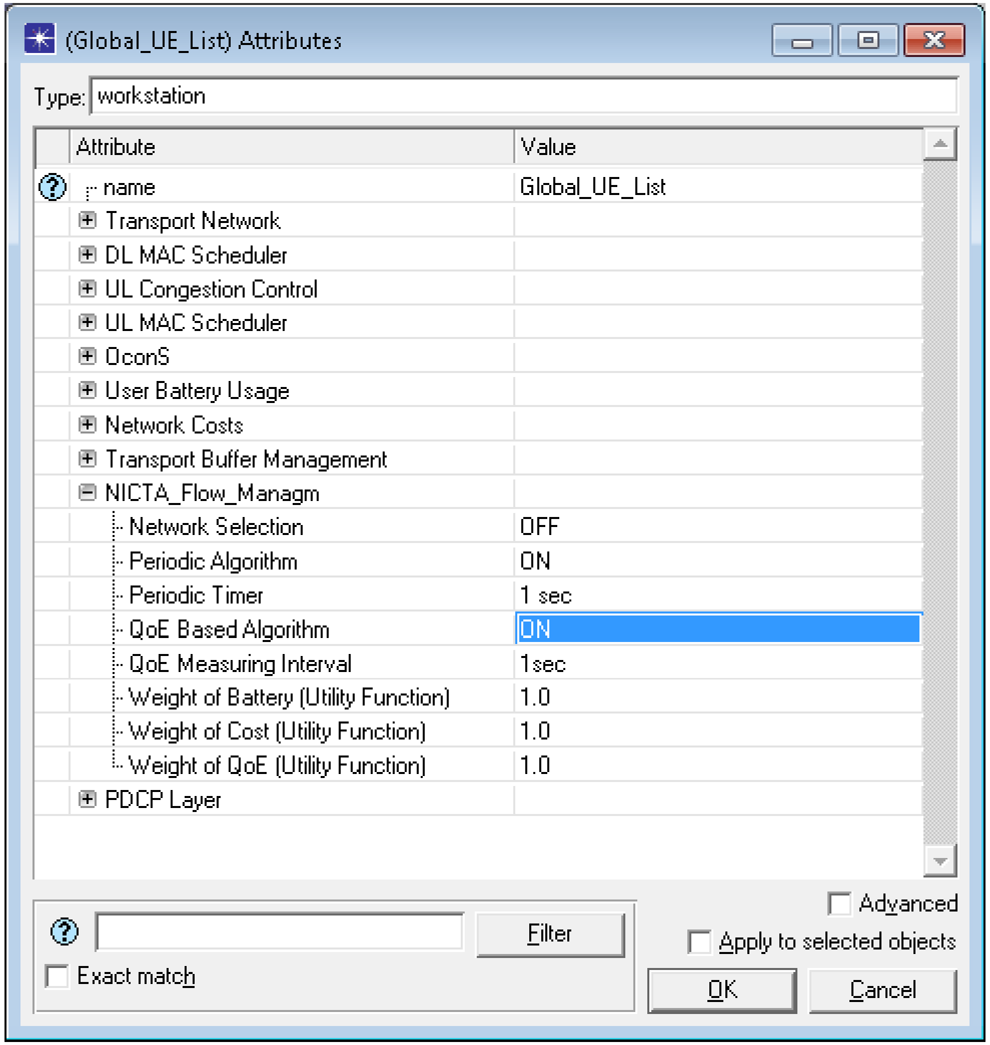
- <u>Elastic Web traffic</u>
  - 1MB web object size
  - Inter-arrival time of 100 s
  - User is moving within WAP1

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

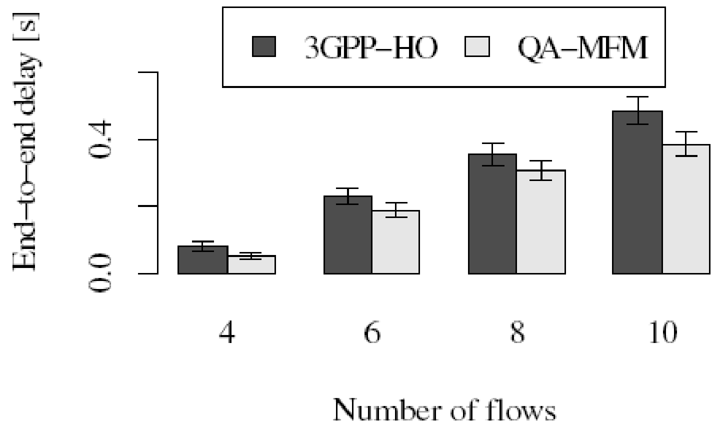
Technology	Power		Price	
	E [%/s]	E' [%/Bps]	M [$/s]	M' [$/Bps]
Cellular	6.5×10^{-3}	2.3×10^{-13}	0	1×10^{-8}
WLAN	3.6×10^{-3}	9.9×10^{-14}	0	0

Configuration of QA-MFM Algorithm

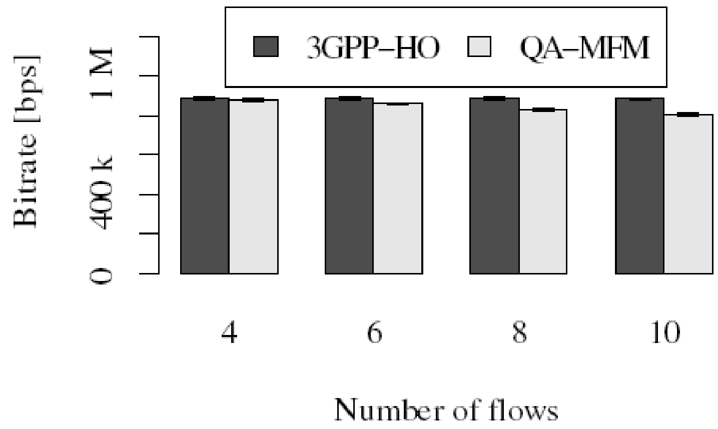
- The configuration for QA-MFM algorithm
  - Periodic triggering scheme (every 1 sec)
  - Weights for Battery, cost and QoE are all equal to 1
  - The user experienced QoE is measured every 1 sec



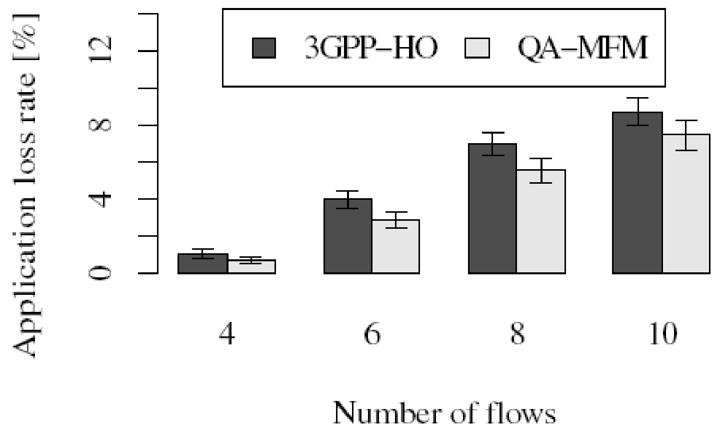
Real-Time Video Traffic Scenario



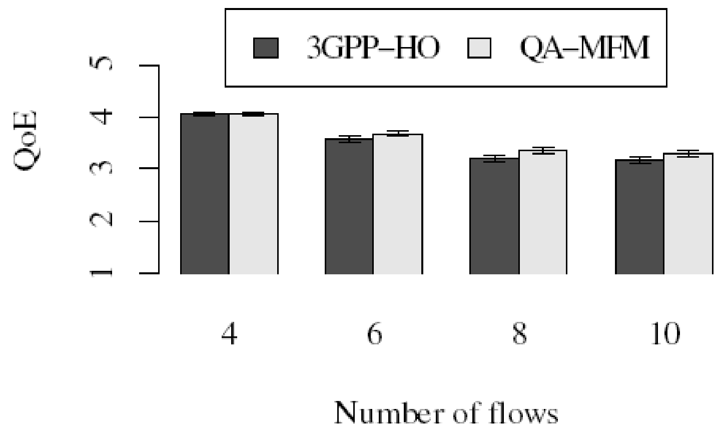
(a) Average end-to-end delay.



(b) Average application bitrate.

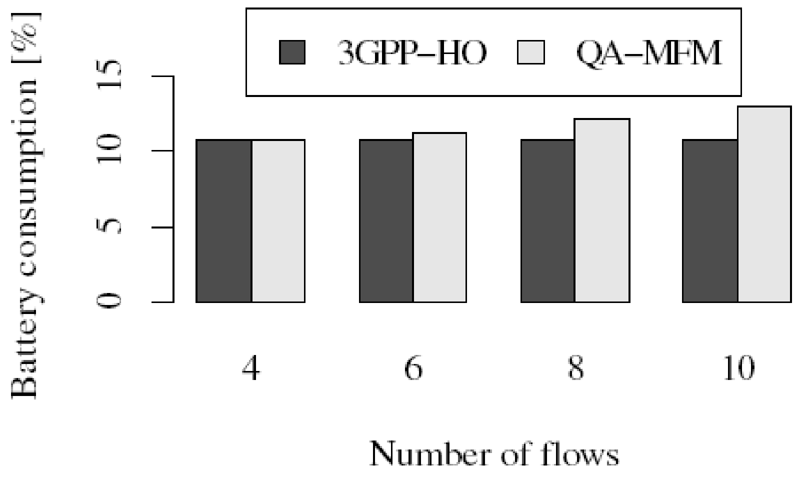


(c) Average application loss.

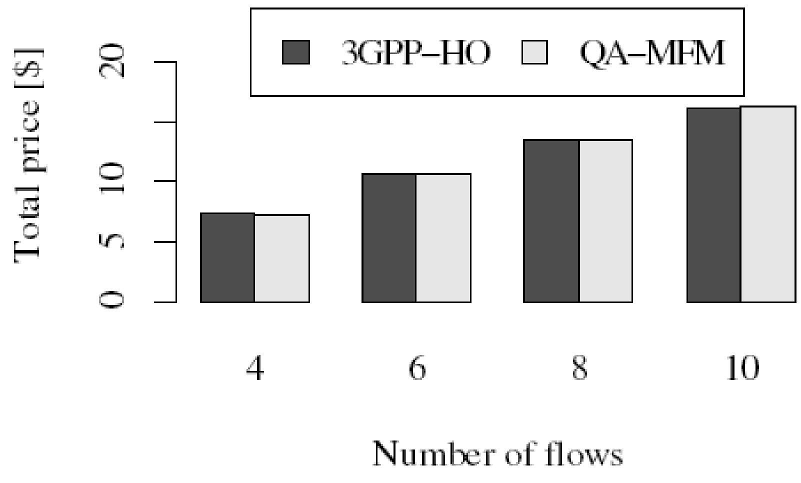


(d) Average QoE.

Real-Time Video Traffic Scenario

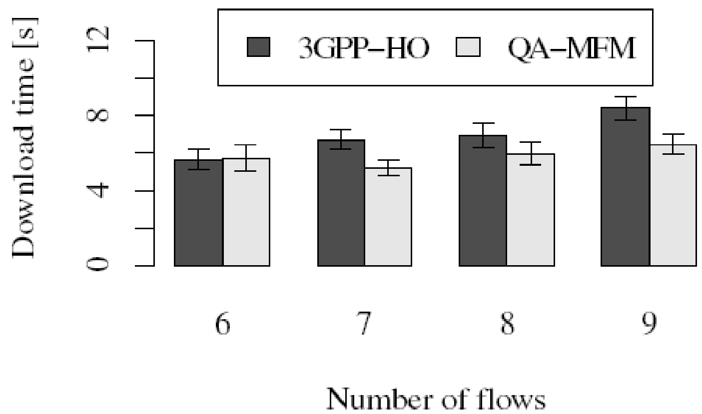


(e) Battery consumption after 2000 s.

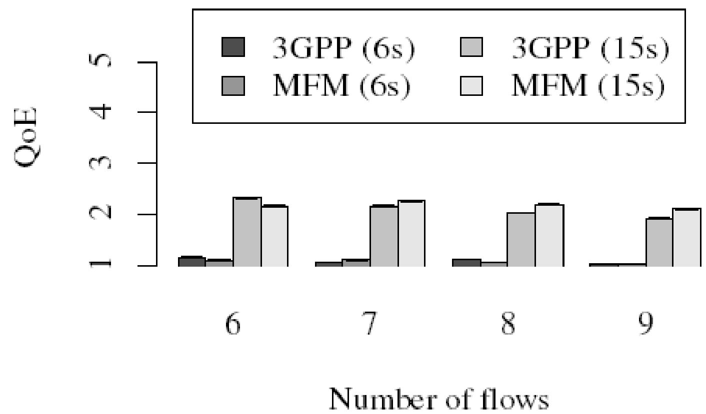


(f) Total monetary cost after 2000 s.

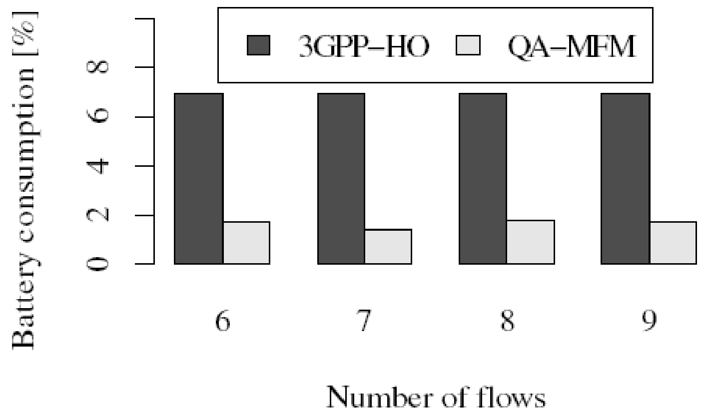
Elastic Web Traffic Scenario



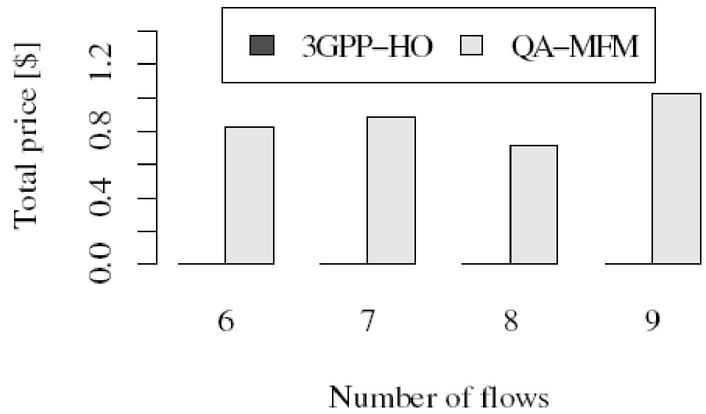
(a) Average download time.



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



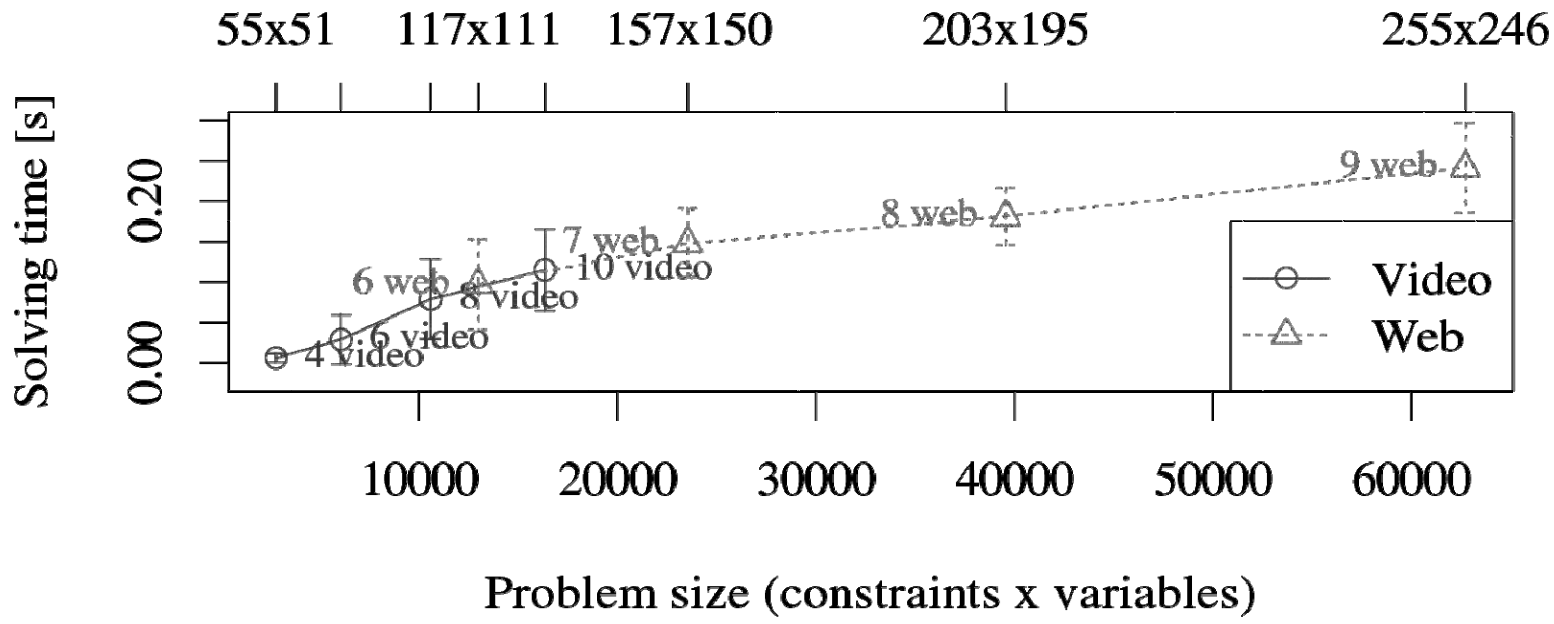
(c) Battery consumption after 2000 s.



(d) Total monetary cost after 2000 s.

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.



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Conclusion and Future Work

Conclusion

- We presented User-Centric Quality-aware Multihomed Flow Management (QA-MFM) mechanism for multihomed mobile devices
  - maximize the QoE, minimize the power usage and network cost
  - The presented results show that this approach provide better trade-offs between different user criteria
- We formulated it as binary integer problem and implemented in the simulator
  - the developed simulation model enables us to more accurately evaluate the flow management approaches when applied to real network scenarios.
  - applying the Linear Programming technique is well-suited and feasible for making real-time decisions in real systems.

Future Work

- Investigate the proper settings for the weights of the objective function
- Further improvement on the implementation such as cross layer signals or optimisation triggering approaches, etc.
- Enable simulations in more realistic scenarios and compare with network-centric approach

References

1. Olivier Mehani, Roksana Boreli, Michael Maher, and Thierry Ernst. “**User- and Application Centric Multihomed Flow Management**". Published in LCN 2011 (pp. 26-34), 36th IEEE Conference on Local Computer Networks, in Bonn Germany, Oct. 2011.
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4. ITU-T Recommendation G.1030. “**Estimating end-to-end performance in IP networks for data applications**." ITU-T SG12, May 2006.
5. ITU-T Recommendation P.800. “**Methods for subjective determination of transmission quality.**" ITU-T SG12, Aug. 1996.
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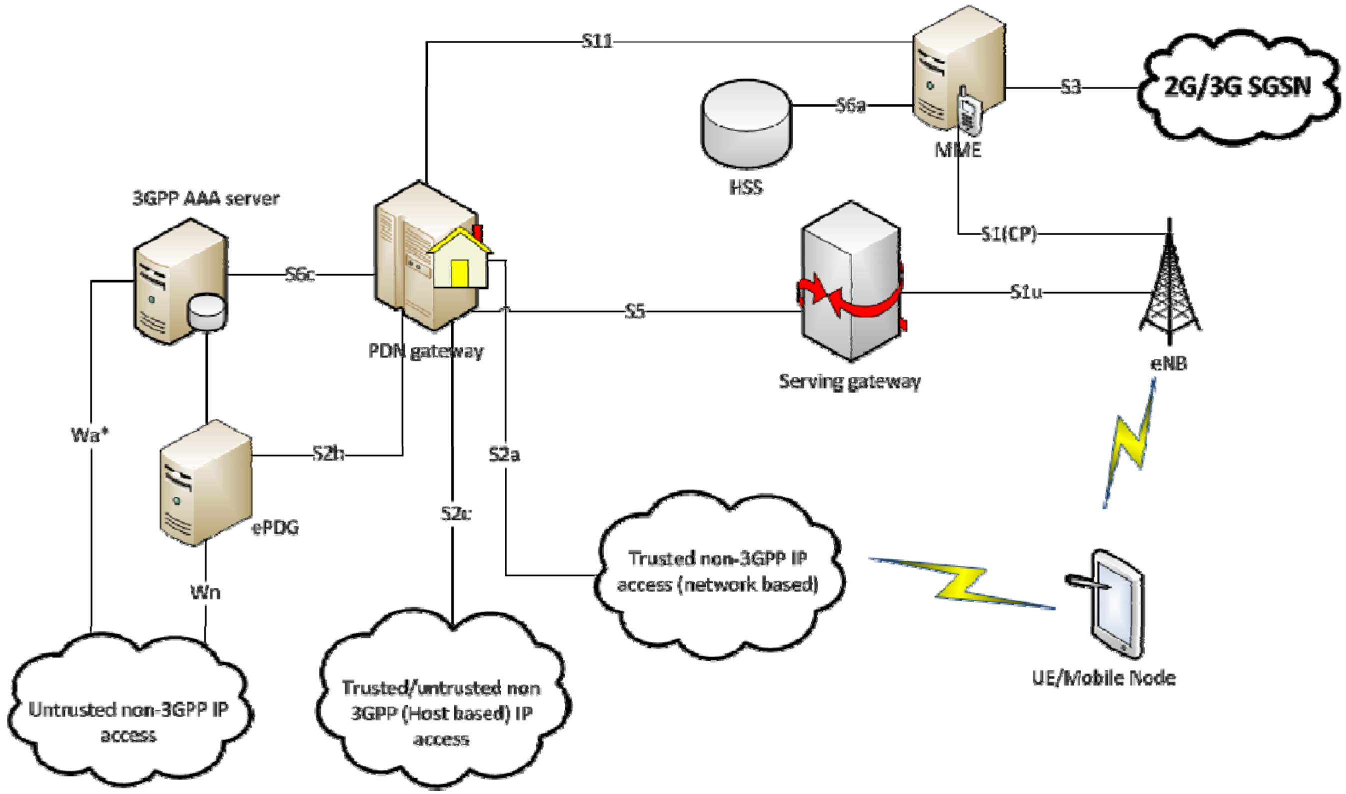
Thank you for your Attention

Any Questions ?

- Backup Slides

Integration of Multiple Access Technologies

- The EPC (Evolved Packet Core) was introduced in 3GPP Release 8 (3GPP TS 23.402) along side with LTE, which allows integration of 3GPP and non-3GPP access technologies (e.g. WiMAX and WiFi) and provides necessary mobility management.



Multihoming

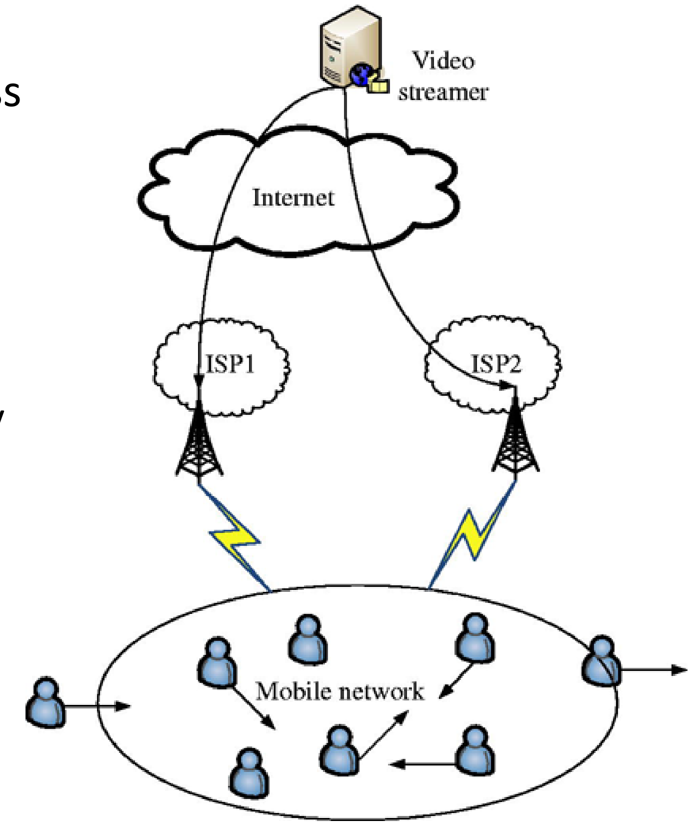
- **Multihoming** is the ability of a host or site to access remote destinations via more than one upstream connections, usually from different ISPs.

Motivation

- For link redundancy: allowing a site to retain connectivity when one of the links fails
- For optimal use of the links to improve network performance in term of delay, available bandwidth and reliability (bandwidth aggregation)

Main Functionalities

- Fault-tolerance and session survivability
- Traffic Engineering (Load Sharing or Load Balancing)
  - to optimize the use of available paths satisfying their performance or policy requirement



Multihoming entities (e.g. end-users) are connected to the Internet through several paths from different ISPs characterized by different QoS

Flow Management Approach

- **Network-Centric Approach:** aim to improve the utilization of network resources by load balancing
  - Typical criteria: network QoS, network costs, resource utilization, etc.

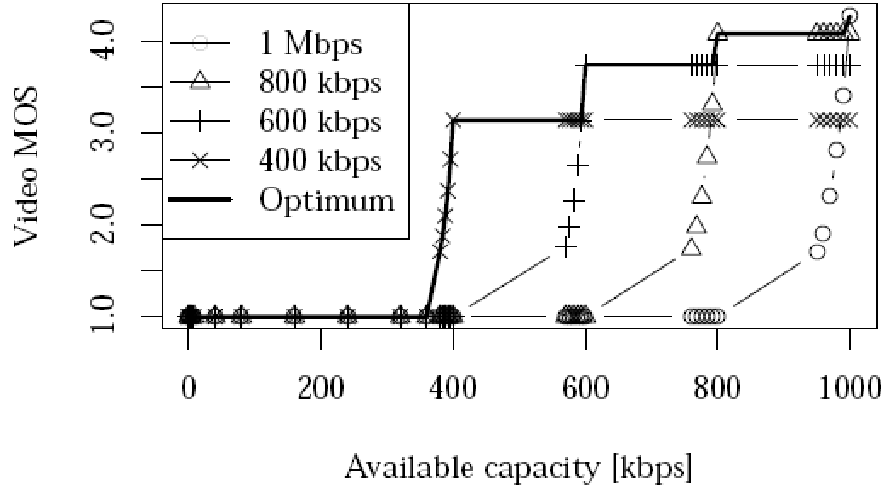
- **User-Centric Approach:** aim to improve the end user performance by exploiting multiple interfaces and access links
  - Typical criteria: application quality (QoE), prices of network, power consumption, user preferences, etc.

- **Hybrid Approach:** consider both network- and user- criteria

QoE Estimations

- The **QoE for video, voice and web flows** is estimated based on the given link QoS using the mathematic models provided by the ITU-T Recommendation G.107 and G.1030 [3, 4]
- QoE is rated by **Mean Opinion Score** (MOS) value [5]

Perception of Quality	MOS
Excellent	5
Good	4
Fair	3
Poor	2
Bad	1



Source: [1] Olivier Mehani, Roksana Boreli, Michael Maher, and Thierry Ernst. "User- and Application Centric Multihomed Flow Management".

Estimate voice quality

$$R = 93.193 - I_s - I_d - I_{e-eff},$$

Estimate video quality

$$V_q = 1 + I_{coding} \exp\left(\frac{P_{plV}}{D_{PplV}}\right),$$

Estimate web quality

$$MOS_{\text{web}} = 5 + 4 \cdot \frac{\ln(WeightedST) - \ln(Min)}{\ln(Min) - \ln(Max)},$$
$$WeightedST = 0.98 \cdot T_3 + 1.76 \cdot T_4,$$

Related Work from ComNets

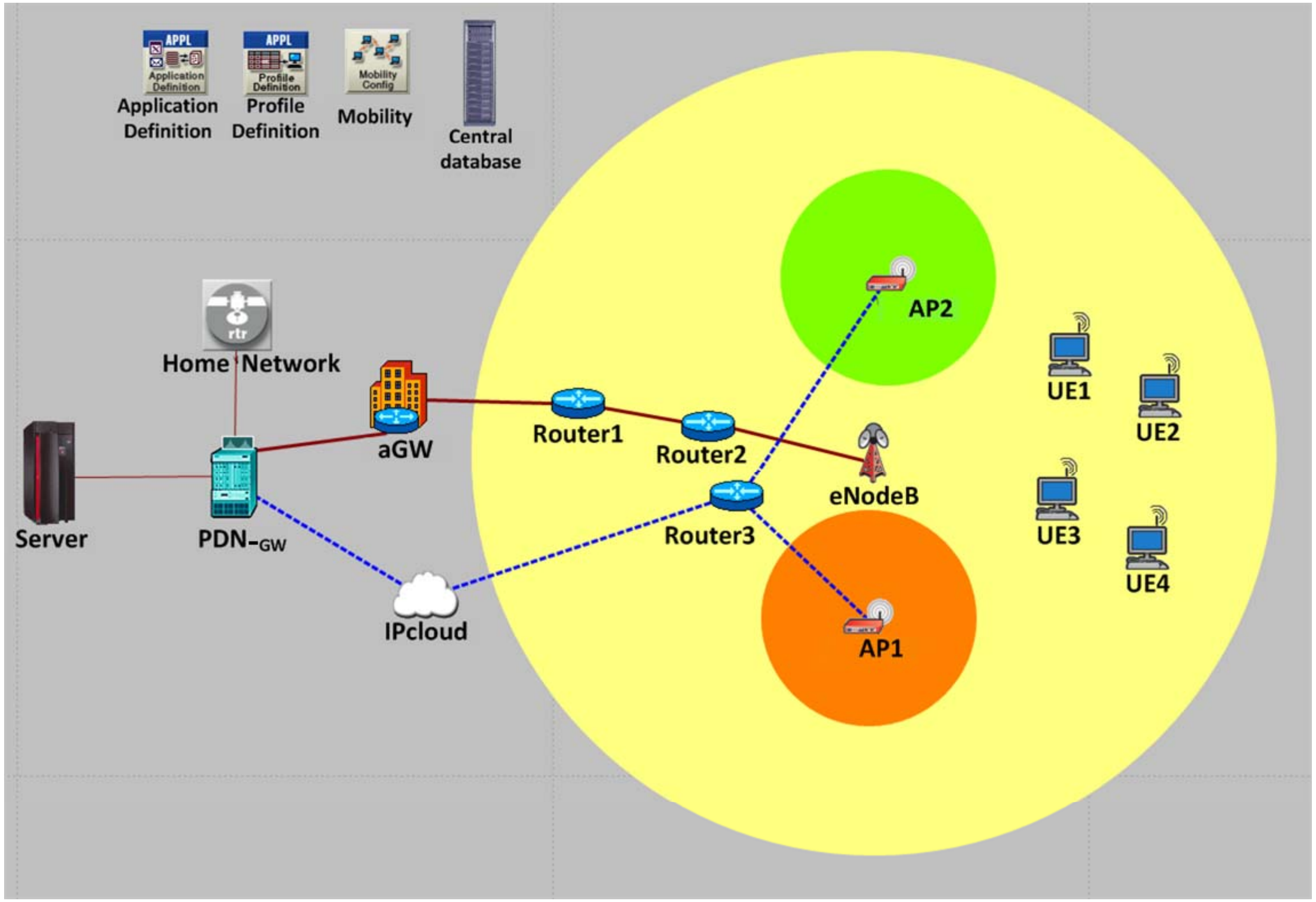
Developed OPNET Simulation Model for 3GPP LTE Interconnected with WLAN

ComNets, University of Bremen / Hamburg University of Technology

Yasir Zaki, Liang Zhao, Umar Toseef, Asanga Udugama

Prof. Andreas Timm-Giel and Prof. Carmelita Görg

Simulation Model for 3GPP LTE Interconnected with WLAN



Source: L. Zhao, Y. N. Zaki, A. Udugama, U. Toseef, A. Timm-Giel and C. Görg, "Open Connectivity Services for Future Networks", presented in CEWIT 2011, New York, USA, Nov. 2-3, 2011

Network-Centric Flow Management Proposed by ComNets

- At the moment the model is focused on the downlink (DL)
  - **OConS layer:** split the traffic of the user in DL at the PDN-GW through two access networks(LTE and WLAN)
  - Decision is network-based (i.e. network-centric)

- Flow Splitting Approaches:
  - Static case: distribute the packets with constant data rate of LTE and WLAN
  - Dynamic case:
    - feeding the traffic over LTE network according to the user connection throughput obtained at the air interface (based on the decision of the MAC scheduler)
    - Feeding the traffic over WLAN network with 15 Mbps constant rate

- Further Work @ ComNets
  - Implement the approach on the uplink (UL)
  - Formulate the flow splitting approach using Linear Programming and implement into OPNET simulator for making decisions
    - Guaranteed Bit Rate (GBR) users: minimize the network resources for required data rate
    - Best Effort users: maximize the achievable user throughput

Simulation Model Assumptions

- Non-roaming trusted SAE architecture between LTE and WLAN
- IPv6 is used
- Mobile IPv6 is used to tunnel user traffic based on care-of-address
- UEs move within the LTE cell (e.g. 375 m radius) according to mobility model and speed given (e.g. pedestrian 3km/h).
- AP is covering a small area (e.g. 100 m radius) in LTE cell
- When UE is within AP hotspot it can transmit data over WLAN as well as over LTE
- LTE is default communication interface

UE Node Model

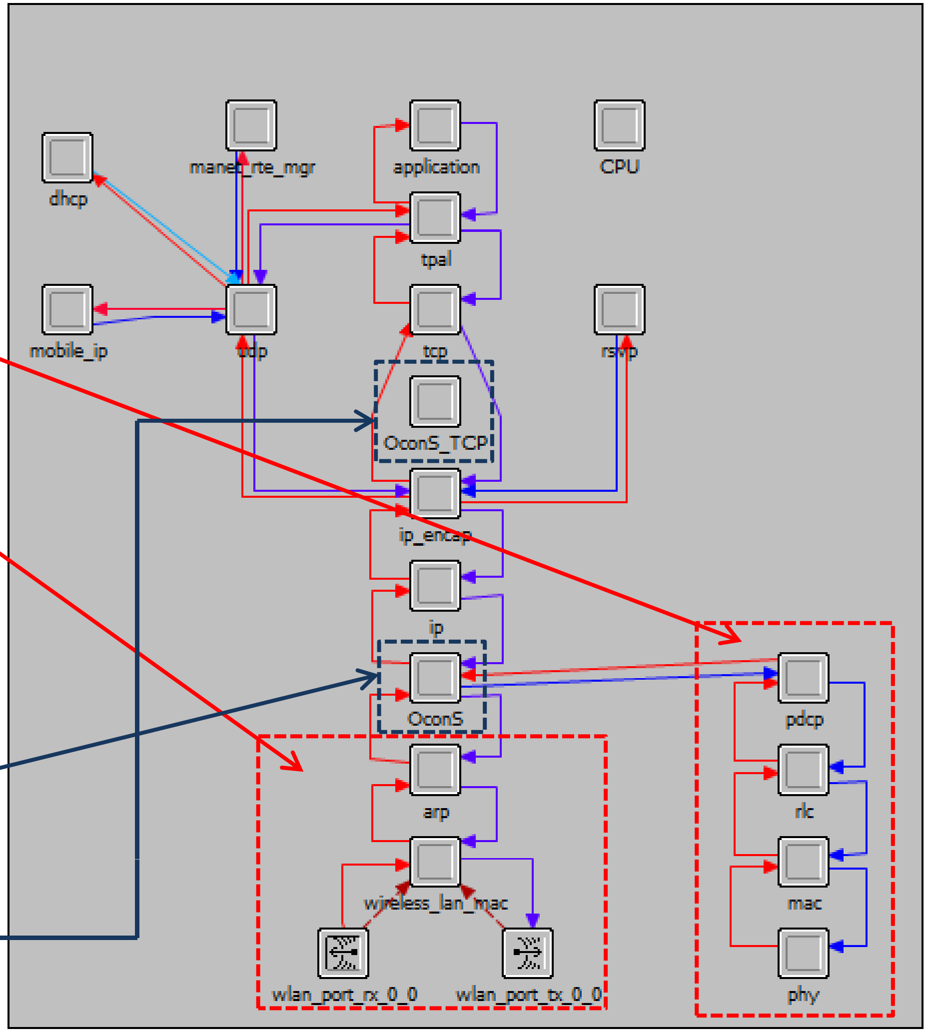
- The UE node has two interfaces:
  - LTE interface
  - WLAN interface

- A new layer (OConS)

is added to the LTE UE stack

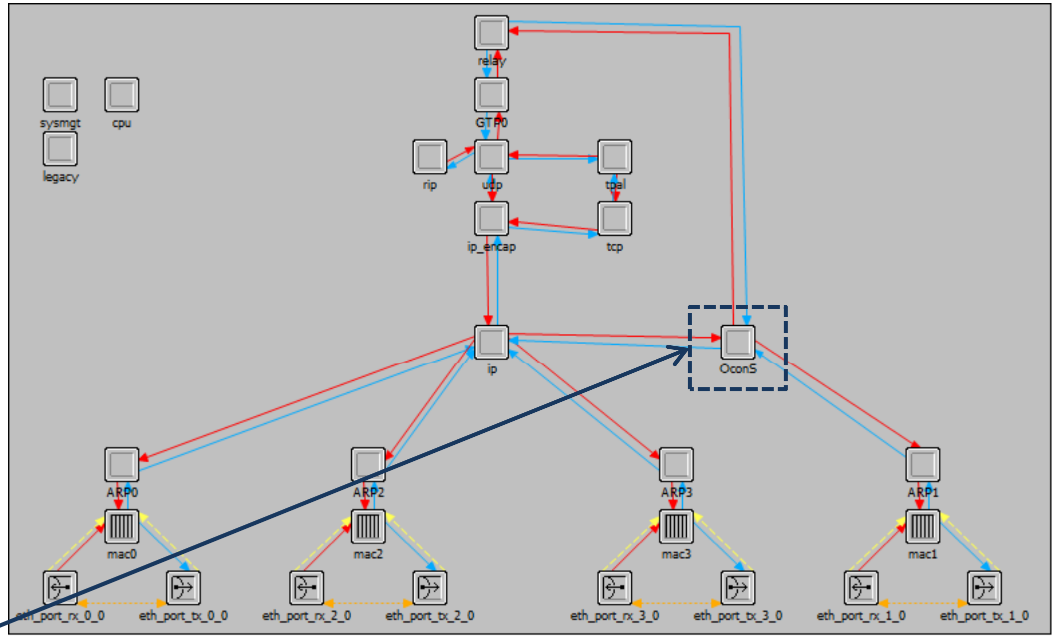
in order to handle the following:

- Used to make decisions for user based control
- Split the traffic of the user in UL
- Collects information for decisions
- Re-ordering of DL TCP packets



PDN-GW Node Model

- The PDN-GW node is the entity where the two access technologies meet.
- The Home Agent runs on this node.
- A new layer (OConS) is added:
  - to make decisions for network based control
  - to split the traffic of the user in DL
  - to collect information for decisions
  - to reorder UL TCP packets



Extending the OPNET Simulator

- Two flow managment approaches have been provided in the model earlier
  - Legacy 3GPP-HO: Select WLAN if available
  - Multi-P Flow Splitting (a Network-centric flow management approach)
- Two MFM approaches were developed in addition in this work
  - Network Selection (NS): Choose the network with the highest capacity
  - Quality-aware multihomed flow management (QA-MFM)
- A practical online decision method was developed for both NS and QA-MFM approaches in this work
  - Formulated the MFM problem as a binary integer program with CPLEX solver and integrated it in OPNET.
  - Implemented a periodic triggering method to call the solver to make decisions at regular intervals (configurable).

Modeling of QA-MFM in OPNET Simulator

- In order to make decisions, all access network conditions (link QoS such as capacity and delay) are measured over time (through the use of frameworks such as IEEE 802.21 or OConS proposed in SAIL Project).
  - WLAN capacity: based on selected PHY model depending on the distance to WAP
  - LTE capacity: based on the measured average SINR and amount of radio resources
  - Given the link capacity per network, we estimate the probable capacities per flow
  - The link delays are estimated based on the measured RTTs
- Providing the estimated link and flow QoS metrics, we estimate the per-flow QoE (considering different application types) following ITU's quality objective models.
- Alongside the energy and costs, the defined objective function is computed and then formulated as a binary integer program for the CPLEX solver.
- The decisions obtained from the CPLEX solver are applied directly in the simulator for network selection, flow distribution and setting the application parameters.
- Evaluate the QoS performance metrics as well as measure the user perceived QoE in the model, thus we can evaluate the impact and performance of the decisions.