Utility Decisions for QoE-QoS Driven Applications in Practical Mobile Broadband Networks

Vasileios Karyotis*, Marios Avgeris*, Michalis Michaloliakos†, Konstantinos Tsagkaris†, Symeon Papavassiliou*
*Institute of Communication and Computer Systems (ICCS)/NTUA
Iroon Polytechniou 9, Zografou, Athens, 15780, Greece
Emails: {vassilis,mavgeris}@netmode.ntua.gr, papavass@mail.ntua.gr
†Incelligent
Syggrou Avenue 189, Nea Smirni, Athens, 17121, Greece
Emails: {michalis.michaloliakos,kostas.tsagkaris}@incelligent.net

***Abstract*—This paper focuses on the design, experimental validation and evaluation of a utility based decision-making approach for wireless (mobile) broadband networks. We extend a utility function framework incorporating flow and user related parameters to be driven by both QoE, QoS parameters and utilize the (mobile) broadband infrastructure of the EU-project MONROE, in order to perform extensive realistic experiments, revealing the operation of the utility function design and quantifying its potentials. We utilize our decision-making approach in two QoE-QoS related applications, namely access network selection and load-balancing in wireless networks with multiple available network interface capabilities. Through experimentation and analysis we investigate the impact of various network aspects, such as mobility, network provider, etc., on access interface switching and relevant applications. Such results can be further exploited for improving the QoE in mobile broadband networks.**

***Index Terms*—Network utility; Quality of Experience; Quality of Service; 5G; Mobile broadband experimental platforms;**

I. INTRODUCTION & CONTRIBUTION

The Internet was initially designed to meet the needs of users [1], and yet today, at the dawn of the 5G era, any criterion with respect to network performance must respond to the question: "how happy does the architecture make the users?". Utility functions have been conceived to formalize such notion of network performance, as a mathematical vehicle towards expressing and measuring the user's degree of satisfaction in a normalized and transparent way, especially in wireless networks, e.g., [1], [2]. Given the heterogeneity of the forthcoming 5G Mobile BroadBand (MBB) networks in terms of physical, architectural and service characteristics, it is extremely important to investigate the potential of exploiting utility function decision-making for improving broadband applications over wireless environments.

Quality-of-Service (QoS) has driven the current evolution of the early generations of mobile networks towards the forthcoming 5G, dictating the specifications of architectures, protocols, services and devices. It was shown that solely satisfying QoS requirements is insufficient, especially for multimedia content services [3], [4]. The concept of Quality-of-Experience (QoE) has been coined towards bridging the gap between users' pragmatic needs and provided services QoS, elevating the users subjectivity and singularity [5]. In this paper, we aim towards demonstrating and validating via experimentation a prominent framework that allows jointly considering network-centric (QoS) and user-centric (QoE) parameters for analyzing and improving network architectures, operations, etc., in MBBs. This will be appealing for operators (striving to satisfy their customers, while optimizing resource consumption and costs), users (who would like to have their experience maximized) and regulators (who are interested for a representative, unitary set of metrics that accurately capture the performance of todays broadband services in practice).

In our previous work [6] we introduced a framework that jointly addresses network/user-centric parameters based on utility functions and Network Utility Maximization (NUM). Despite the theoretical promise of these results, it is necessary to validate, and more importantly, practically utilize such framework in designing novel protocols and applications in realistic MBBs. In this paper, we focus on the practical validation of this framework and experimenting with it in real networks, while quantifying its performance potentials. First we develop a more specific form of the proposed utility-based decision framework, and then we utilize this design in improving access network selection and concurrent multi-path routing. We perform experiments over the infrastructure of the MONROE EU-project, utilizing operational static or mobile nodes with multiple available network access interfaces. Through the obtained results, we demonstrate how the proposed framework can be used in practice and how it can be utilized for improving the design of applications in MBB networks.

The rest of this paper is organized as follows. In section II relevant works are presented, while section III presents the designed utility function framework employed for decision-making in MBBs. Section IV presents the application of the designed framework for network access selection, and finally, section V provides results for an application of concurrent multipath routing.

II. RELATED WORK

Considerable work has been devoted to utility-based frameworks addressing QoS/QoE related aspects in wireless mobile networks. Examples include [7]–[9], focusing on network

978-1-5386-7272-3/18/$31.00 ©2018 IEEE

optimization. The work in [9], aimed at the computation of the optimal flow rates via maximization of the sum of utility functions, each assigned to a network flow. Topology control through a utility framework is achieved in [8], where each user determines its optimal transmission power by maximizing its own utility function through a game theoretic approach. In [7], the utility approach was extended to exploit social network characteristics in resource allocation optimization. In this paper, we extend such approaches by considering jointly QoE, QoS related parameters in the designed utility framework.

At the same time, adapting network access among various available interfaces has attracted considerable attention [10]. Various approaches have been suggested for determining access network switching. In [11], the authors make use of Multi-Attribute Decision Making (MADM) algorithms to dynamically select the optimal interface after ranking the available candidates, following a Q-Learning-based approach to adapt to QoE variations. Using utility functions for network selection has proven a promising direction [10]. In this work, we adopt this approach and design a utility function that takes into account jointly QoS and QoE related parameters.

Multipath routing has been identified to play a significant role in an effort to achieve reliability, availability and efficiency in a MMB environment where the data transfer occurs through a number of multiple paths from a source to a destination. In [12], the authors proposed a multipath routing approach that takes into account QoS requirements of different real-time applications. They classified the real-time traffic into three specific categories and route priority classes with guaranteed QoS through specific paths. Relevant works related with QoS-enabled multipath routing approaches focus on application and architecture requirements along with their respective routing strategies [13]–[15] targeting the satisfaction of the performance requirements for different applications. However, there are additional criteria that should be considered when designing multipath routing strategies for MMB networks, like QoE-related parameters. In this work, we extend these approaches by considering both QoS-QoE parameters for the development of a more user-centric routing decision.

III. UTILITY FUNCTION DECISION FRAMEWORK

Our goal is to exploit utility functions for advanced decision-making, such as improved network access selection, or improving applications such as multipath concurrent routing. In this section, we describe and develop the utility framework, while the next sections describes the experimental setup and obtained results.

A. General Utility Function Form

For each user, we adopt the general utility function of [6], consisting of two parts. The first containing flow-specific parameters and the second containing user-specific ones:

$$U(i) = \underbrace{\sum_{d} [A(i,d)U_f(p_f,i,d) - B(p_f,i,d)]}_{\text{Flow related part}} + \underbrace{[C(i)U_n(p_n,i) - D(p_n,i)]}_{\text{User related part}} \quad (1)$$

TABLE I
PARAMETER CLASSIFICATION FOR USER UTILITY FUNCTION $U(i)$.

Flow-related	User-interest
delay d	available bandwidth b_a
transmission rate r	required bandwidth b_r
throughput u	priority p_r
packet loss p	number of stalls i
jitter j	TCP setup time t_{TCP}
SNR s	max. transmission rate $r_{\max}$
round-trip-time (RTT) r_{tt}	
TCP retransmissions t_r	
out-of-order packets o_p	

Parameters $p_f,\ p_n$ denote the flow and user related parameters, respectively. $U_f(p_f,i,d)$ is the part assigned to a flow with source i and destination d for parameter p_f, and similarly, $U_n(p_n,i)$ is the part assigned to user i for its corresponding parameter p_n. $A(i,d),\ C(i)$ are multiplicative coefficients (independent of $p_f,\ p_n$), while $B(p_f,i,d),\ D(p_n,i)$ can serve as penalty functions (depending on $p_f,\ p_n$ correspondingly).

The flow related coefficients ($A(i,d),\ B(p_f,i,d)$) express the determined importance of the service of a flow (with source user i and destination user d). The lower importance of a flow can be represented via proper specification of A, B, so that the parameters assigned to this flow receive “worse” values compared to the corresponding values of more important flows. The user related coefficients ($C(i),\ D(p_n,i)$) express the importance of user i in the resource management.

B. Parameters and Functional Forms for Utility Functions

There are many possible parameters of interest that can be employed for the flow or user related part of the utility function. The user-related parameters are denoted as such, because of their importance for the perceived QoE by users, while flow-related parameters are deemed more important for the received QoS. Table I summarizes the most notable ones, segregating them as per their flow or user relevance.

Most of the parameters included in Table I are above layer 2, namely in the network, transport or even higher layer. The reason for this design choice is that we wanted the utility framework as generic as possible, and eventually independent of the underlying wireless transmission technology, i.e., LTE, WiFi, etc., while remaining usable for mobile broadband applications, e.g., video streaming and wireless interface selection. Furthermore, we wanted it to be indicative of features that pertain to the QoE and QoS as perceived by the user, features which typically tend to be in the higher protocol layers.

We have also identified candidate functional forms for the conventional utility functions for various purposes. Many of these functional forms have been suggested in relevant works [6], [10], [16], [17]. Table II, summarizes these functional forms, where $x^{\max}$ is the maximum value of parameter x used in the utility function. Parameters a, b, c are constant.

One key requirement is that the selected functional forms should satisfy the following constraints:

$$\frac{\partial U}{\partial p_i} \geq 0,\ \lim_{p_i \to 0} U(i) = 0,\ \lim_{p_i \to \infty} U(i) = 1, \quad (2)$$

TABLE II
FUNCTIONAL FORMS FOR USER UTILITY FUNCTION $U(i)$.

Function	Formula
Logarithmic	$U_i(x) = \log(x)$ or $U_i(x) = \frac{\log(1+c \cdot x)}{\log(1+c \cdot x^{\max})}$
Sigmoidal	$U_i(x) = \frac{1}{1+e^{-x}}$
Exponential	$U_i(x) = \begin{cases} 1 - e^{-a \cdot x}, & a \neq 0 \\ x, & a = 0 \end{cases}$
Modified sigmoidal	$U_i(x) = \frac{\left(\frac{x}{c}\right)^a}{1+\left(\frac{x}{c}\right)^a}$
Linear	$U_i(x) = a \cdot x + b$

The form of utility (1) is presented in the more general form. In practice, a more targeted form, relevant to the involved application suffices. For the experimentation we have employed a more particular and simpler form that allowed demonstrating the potentials of the framework.

C. Practical Utility Form

In this subsection we present the specific design of the QoS and QoE related parts of the user utility, following the selection of key parameters of interest. We have considered for our experimentation the following parameters: delay d, transmission rate r, throughput u, SNR s, jitter j, packet loss p, number of stalls of the streaming flow i. The form of the user utility function taking into account the above parameters cumulatively via vector $\mathbf{p}$, and using appropriate functional forms from Table II is the following:

$$\begin{aligned} U_i(\mathbf{p}) = {} & w_1 \left[\max\left\{1 - \frac{\log(1+c_1 d)}{\log(1+c_1 d_{\max})}, 0\right\}\right] + w_2 \frac{\left(\frac{r}{c_2}\right)^2}{1+\left(\frac{r}{c_2}\right)^2} \\ & + w_3 \frac{\left(\frac{u}{c_3}\right)^2}{1+\left(\frac{u}{c_3}\right)^2} + w_4 \frac{\left(\frac{s}{c_4}\right)^2}{1+\left(\frac{s}{c_4}\right)^2} + w_5 \left[\max\left\{1 - \frac{\log(1+c_5 j)}{\log(1+c_5 j_{\max})}, 0\right\}\right] \\ & + w_6 \left[\max\left\{1 - \frac{\log(1+c_6 p)}{\log(1+c_6 p_{\max})}, 0\right\}\right] + w_7 \left[1 - \frac{\left(\frac{i}{c_7}\right)^2}{1+\left(\frac{i}{c_7}\right)^2}\right] \end{aligned} \tag{3}$$

Parameters $w_1, ...w_7$ denote constant weight factors used to regulate the importance of each parameter in the decisions made. They can be selected according to design objectives. The user utility function is augmented with a directly QoE-relevant term yielding the form:

$$U_i\left(q_e, \mathbf{p}\right) = w_a \cdot q_e + w_b \cdot U_i(\mathbf{p}) \tag{4}$$

where q_e denotes the QoE rating value (obtained from the QoE-QoS table described in the sequel), and w_a, w_b are weight factors, which in our case are chosen to be both equal to 0.5, indicating equal weight of QoE value/QoS parameters in the decisions made. In other applications, unequal weights can be employed depending on the importance of each factor in the application considered. The utility function described above has been exploited in two applications over MBBs in MONROE, regarding the selection of the most appropriate access interface among multiple ones, and for concurrent multipath routing. Also, we have the option of computing the QoS related parameters via UDP or TCP based measurements.

IV. ACCESS NETWORK SELECTION

In this section we describe the experimental setup and results obtained from the study of network access selection. The system configuration is shown in Fig. 1. A MONROE node is selected having available two LTE interfaces that can be used in parallel. Each node also has an LTE in parallel with a WiFi interface. The two parallel LTE interfaces provide access to the Internet via two different providers in each of four different countries, namely Norway, Spain, Sweden and Italy. As mentioned earlier, these nodes are either mobile (deployed on trains, trucks and buses) or static.

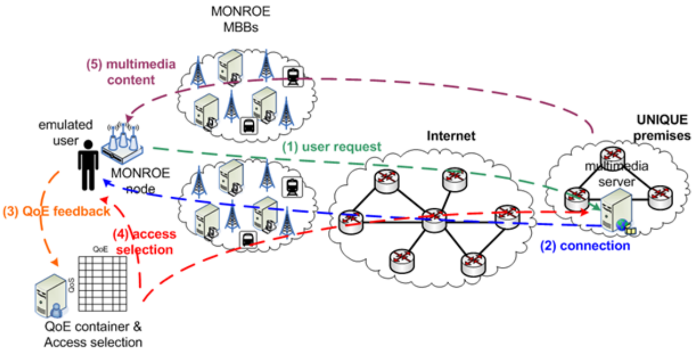

Fig. 1. Experimental topology setup employed for interface selection evaluation.

A user initiates a traffic flow from a MONROE node towards a remote server, which in our case resides in our premises. Upon establishment of the connection, the user acquires various QoS related metrics regarding the parameters of interest, mentioned before as $\mathbf{p}$, by utilizing an iPerf3 client-server architecture [18] deployed solely for this purpose. Thus, a QoS profile is created reflecting the objective network performance indicators that the user receives from the network. This profile is subsequently used as a reference to identify the corresponding QoE value that a real user would provide and ultimately determine the superior interface. The QoE value is obtained by calculating the minimum Euclidean distance between the user's QoS profile and the QoS profiles contained in a QoE-QoS table, which we compiled offline, performing experiments with real users.

During the latter experimentation, the users were providing QoE values while we logged the corresponding QoS profiles they experienced in a controlled wireless environment. The reason for this approach lies in a restriction of the MONROE architecture, which does not currently allow for accessing the MONROE nodes remotely and thus obtaining real-time a QoE value. Consequently, we relied on an emulated approach, where QoE-QoS profiles have been associated offline and used in an automated fashion during the actual experimentation over the MONROE platform.

The MONROE platform hosts experiments configured as Docker containers. Hence this experimental setup has been built as a Docker image and is publicly available in the Docker Hub[1]. The source code is openly accessible on GitHub[2].

We have executed various experimental scenarios in which we investigate the effectiveness of switching to the wireless ac-

---

[1] https://hub.docker.com/r/mavgeris/monroe_exp/

[2] https://github.com/maravger/monroe-network-selection

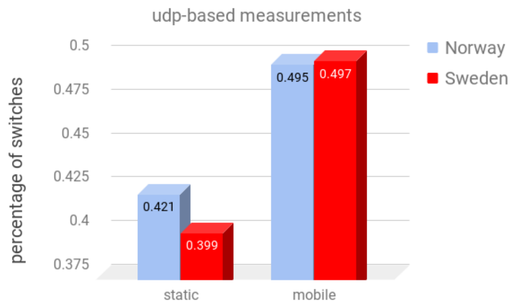

Fig. 2. Wireless access interface switching behavior based on UDP measurements for static and mobile scenarios.

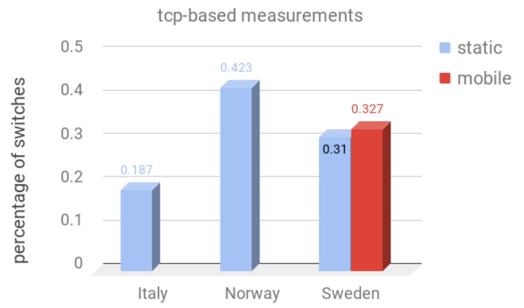

Fig. 3. Wireless access interface switching behavior based on TCP measurements for static and mobile scenarios.

cess interface with best overall ranking (QoE-QoS combined) and the stability of this switching with respect to transmission parameters and different service providers. We have performed two broad sets of experiments, the first where the QoS-related parameters of the employed utility function are computed using UDP packet based iPerf measurements (Fig. 2), and a second where the computation of QoS related parameters of the utility function is based on TCP packet based iPerf measurements (Fig. 3).

Fig. 2 presents the percentage of interface switchings taking place in an interval of 1000sec. for static and mobile nodes, with access to two different LTE providers in two different countries, namely Norway and Sweden. Time is slotted and at the beginning of each slot each node evaluates the node utility function employed and makes a decision on whether it should switch wireless provider or not. Valuable observations can be made regarding the behavior of our approach and the quality of access offered by the various providers in the two countries with respect to the QoE-QoS employed framework.

Mobile node scenarios present more wireless access switches, as expected, since the mobile channel varies more, affecting the overall utility value computed. Our framework, determines each time the best access interface. With respect to the providers per country, in Norway, comparing the quality of access experienced on average by users between the static and mobile scenarios leads to an approximately 18% of switching, while in Sweden a wireless access interface switching of approximately 25% is observed. Access in Sweden from a static node seems to be better than in Norway, while access from a mobile node is almost identical. In both countries, the percentage of switches is determined in the interval [0.4-0.5], indicating that the combined QoE-QoS quality varies considerably. Nevertheless, our framework identifies such variations and adapts connectivity to the best access interface.

It should be also noted that with respect to the sequence of switches observed in all of the above scenarios, an emerging pattern in all scenarios was that there were short periods of constant switching, and longer ones with more stable behavior. This is due to the nature of the wireless channel, which appears to have a block-fading behavior. Our framework is capable of capturing this nature and adapt access properly.

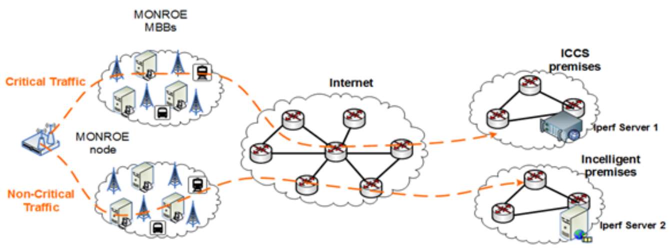

Fig. 4. System employed for concurrent multi-path routing.

Similar results are presented in Fig. 3, including static scenarios in 3 different countries (Italy, Norway and Sweden) and one mobile in Sweden, this time using a TCP packet based iPerf measurement for the QoS-related parameters. TCP based measurements are less preferable due to their overhead, but offer greater flexibility in computing QoS-related parameters.

It can be observed that different behaviors emerge among the three countries, with Italy emerging as the one where providers offer the more stable connections and Norway the most volatile. Comparing the results regarding Sweden with those based on UDP measurements (Fig. 2), the behavior in static scenarios appears similar to that observed when using UDP based measurements, while the behavior regarding mobile scenarios exhibits small differences. These outcomes indicate the effectiveness of the proposed framework for both assessing wireless connection quality in MBBs, and adapting operation towards achieving better experience for the users.

V. TRAFFIC LOAD BALANCING

In this section, we describe the experimental setup and results obtained from the study of a concurrent multipath routing application developing on top of the previous utility-based network access selection approach. Fig. 4 depicts the scenario that we executed during the concurrent multipath routing phase of the experiment. In particular, we managed to perform concurrent multipath routing, where the selection of the available interfaces that are used to forward the classified traffic is based on the utility-based decision-making.

The user equipment is a MONROE node that provides three simultaneously available interfaces for use. The one that is characterized as a local area network interface and two LTE that are connected to service MBB Telecom providers and are utilized in parallel to route traffic to the public Internet. For the needs of this experiment, we used two servers that are located in both ICCS and Incelligent premises (VMs with public IPs) and are accessible by any MONROE node of any relevant country. IPerf servers are configured to accept network traffic from the MONROE node as the "end-to-end" network paths are changing dynamically based on the proposed algorithm.

As a start, we select an available MONROE node and download the pre-configured container (public in the Docker Hub at https://hub.docker.com/r/mmichaloliakos/monroeexp/) with the software extension for concurrent multipath routing included. The utility-based network access selection starts measuring and provides the ranking for the interface of each Telecom Provider. The concurrent multipath routing mechanism perceives the ranking of the available interfaces and changes the routing table of the MONROE node by using the optimal network path to forward the critical traffic and the remaining interface to forward the non-critical traffic. Critical traffic is forwarded to the Incelligent Public Server on port 8844, while non-critical traffic is forwarded to the ICCS Public Server on port 5201. During the experimentation, network access selection is modified based on the changes of QoS-QoE mapping and the ranking of each MBB interface. Thus, the routing decision is associated with the relevant ranking and the routing table is changing respectively.

In Figs. 5 and 6, the total amount of classified traffic that was forwarded from the relevant MBB Telecom Providers from Norway and Spain, respectively, is depicted. The template for the utility-based interface selection software (as independent module) can be downloaded from: https://bitbucket.org/incelligent/concurrent-routing.

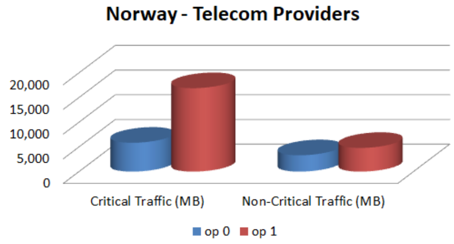

Fig. 5. Total amount (MB) of traffic forwarded concurrently by Norwegian Telecom Providers.

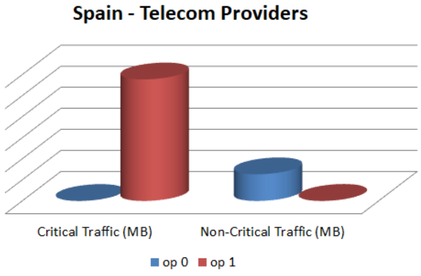

Fig. 6. Total amount (MB) of traffic forwarded concurrently by Spanish Telecom Providers.

ACKNOWLEDGMENT

This work was funded by the EU's Horizon 2020 research and innovation programme under grant agreement No. 644399 (MONROE) through the open call project UNIQUE. The views expressed are solely those of the authors. The work of Dr. Karyotis and Mr. Avgeris was also supported by ICCS Research Award under Grant Number 65020601.

REFERENCES

[1] S. Shenker, "Fundamental Design Issues for the Future Internet", *IEEE JSAC*, vol. 13, no. 7, pp. 1176-1188, Sept. 1995.

[2] M. Chiang, S.H. Low, A.R. Calderbank, J.C. Doyle, "Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures", *Proc. IEEE*, vol. 95, no. 1, pp. 255-312, Jan. 2007.

[3] Q. Zhang, C.W. Chen, P. Frossard, K. Wu, "Quality-of-Experience-Aware Design in Next-Generation Wireless Networks", *IEEE Network Mag.*, pp. 4-5, Nov./Dec. 2015.

[4] M. Suefert, S. Egger, M. Slanina, T. Zinner, T. Hossfeld, P. Tran-Gia, "A Survey on Quality of Experience of HTTP Adaptive Streaming", *IEEE Commun. Surv. & Tut.*, vol. 17, no. 1, 1st quarter 2015.

[5] G. Aristomenopoulos, V. Kaldanis, G. Katsaros, S. Papavassiliou, "Experimentally driven Quality of Experience-aware Multimedia Content Delivery in Modern Wireless Networks", *I.J. Comm. Sys.*, Jan. 2015.

[6] E. Stai, V. Karyotis, S. Papavassiliou, "Exploiting Socio-Physical Network Interactions via a Utility-based Framework for Resource Management in Mobile Social Networks", *IEEE Wirel. Com. Mag.*, vol. 21, no. 1, pp. 10-17, Feb. 2014.

[7] V. Kulkarni, M. Devetsikiotis, "Social Distance Aware Resource Allocation in Wireless Networks", *Proc. IEEE GLOBECOM*, Dec. 2009.

[8] A. Manolakos, V. Karyotis, S. Papavassiliou, "A Cross-Layer-Based Topology Control Framework for Wireless Multihop Networks", *IEEE Trans. Veh. Tech.*, vol. 61, no. 6, pp. 2858-2864, July 2012.

[9] L. Xiaojun, N.B. Shroff, R. Srikant, "A Tutorial on Cross-Layer Optimization in Wireless Networks", *IEEE J. Sel. Areas Commun. (JSAC)*, vol. 24, no. 8, pp. 1452-1463, Aug. 2006.

[10] L. Wang, G.-S. Kuo, "Mathematical Modeling for Network Selection in Heterogeneous Wireless Networks - A Tutorial", *IEEE Commun. Surveys & Tut.*, vol. 15, no. 1, 1st quarter 2011.

[11] M.A. Senouci, M.S. Mushtaq, S. Hoceini, A. Mellouk, "TOPSIS-based Dynamic Approach for Mobile Network Interface Selection", *Comp. Netw.*, vol. 107, pp. 304-314, 2016.

[12] A. Talele, P. Mehta, Y. Gadade, A. Mundhe, and A. Kandhare, "A QoS-Aware Multipath Routing Protocol for Wi-Fi Based Long Distance Mesh Networks", *2nd Int' Conf. Emerging Tech. Trends in Elect., Commun. Netw.*, Dec. 2014.

[13] M. Radi, B. Dezfouli, K. Abu Bakar, and M. Lee, "Multipath Routing in Wireless Sensor Networks: Survey and Research Challenges", *MDPI Sensors Journal*, vol. 12, no. 1, pp. 650-685, Jan. 2012.

[14] S. Ehsan, B. Hamadoui, "A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks", *IEEE Commun. Surveys & Tut.*, vol. 14, no. 2, pp. 265-278, 2nd Quarter 2012.

[15] N. Mishra, A. Kumar, "Comparative Analysis: Energy Efficient Multipath Routing in Wireless Sensor Network", *Int'l J. Comp. Science & Mobile Comp. (IJCSMC)*, vol. 3, no. 9, pp. 627-632, 2014.

[16] P. Casas, M. Seufert, F. Wamser, B. Gardlo, A. Sackl, R. Schatz, "Next to You: Monitoring Quality of Experience in Cellular Networks from the End-devices", *IEEE Trans. Netw. & Service Man.*, vol. 13, no. 2, pp. 181-196, June 2016.

[17] M. Seufert, P. Casas, F. Wamser, N. Wehner, R. Schatz, P. Tran-Gia, "Application-Layer Monitoring of QoE Parameters for Mobile YouTube Video Streaming in the Field", *Proc. 6th IEEE Int'l Conf. Comm. & Electronics (ICCE)*, July 2016.

[18] A. Tirumala, "Iperf: The TCP/UDP Bandwidth Measurement Tool.", *http://dast. nlanr. net/Projects/Iperf/*, 1999.