On User-Centric Tools for QoE-Based Recommendation and Real-Time Analysis of Large-Scale Markets

Michalis Katsarakis, Georgios Fortetsanakis, Paulos Charonyktakis, Alexandros Kostopoulos, and Maria Papadopouli

ABSTRACT

This article focuses on mechanisms that empower users with quality of experience recommendations and smart real-time analytics. It presents a user-centric recommendation system (called u-map) that enables users to collect network measurements and subjective opinion scores about the performance of various services. It also cross-correlates measurements obtained by u-map to provide geo-statistics, user profiles, and quality of experience prediction models for different services. The article also presents CoRLAB, a modular multi-layer framework for modeling and assessing various markets, services, and their evolution under a diverse set of customer populations and conditions. U-map feeds CoRLAB with user measurements and feedback in (semi) real-time. The article discusses how u-map and CoRLAB have been used to analyze telecommunication markets and services. It highlights the main research results, challenges, and potential research directions.

INTRODUCTION

New paradigms in both the wholesale and retail service markets are being formed and accelerated by technological advances (e.g., in networking, virtualization), the booming of content delivery, and regulatory changes on access and competition rules. These paradigms can enrich the roles of service providers, differentiate traditional pricing schemes, and enable new business models. For example, cost reductions and higher efficiency can be achieved through increased multiplexing due to the pooling of existing infrastructure, resource sharing, crowdsourcing, and partnerships among providers.

The advances in wireless and sensor networks, cloud services, and smartphones have enabled the monitoring of large-scale dynamic environments and real-time data analysis. Crowdsourcing and participatory sensing in large-scale systems provide the capability to monitor, in real time, the *quality of service* (QoS),

as well as to estimate and predict the perceived *quality of experience* (QoE). Based on this information, personalized recommendations can be provided to customers for the appropriate services according to their profiles. Moreover, smart data analytics can enable service providers to improve their services. This article focuses on telecommunication markets, although these issues are also relevant in a plethora of other application domains and markets.

According to forecasts, in the following years, mobile data traffic will exceed several exabytes per month worldwide, while by 2016, video will be approximately 86 percent of the global consumer traffic [1]. Moreover, the relationships between users and providers are becoming more flexible. These changes will make their decision processes more complex. At the same time, the Body of European Regulators for Electronic Communications (BEREC) in recent reports envisages measures for *consumer empowerment*, boosting *consumer choice*, *network transparency*, and developing mechanisms for *data collection* and *analysis*. Operators are required to choose a more rigorous approach, increase operational efficiency, and roll out new services in a cost-effective manner. By providing meaningful feedback to customers and providers, the performance of telecommunication markets can be significantly improved in terms of QoE, revenue, and social welfare.

These trends motivated our research in analyzing telecommunication markets. Specifically, we have developed u-map [2], a user-centric reviewing system that enables users to monitor various services (running on smartphones) and collects user opinion scores about their performance (Fig. 1). These data are uploaded on a geo-database in a crowdsourcing manner. Data analytics can then be applied for customer profiling, new service planning and testing, pricing, and market refinements. U-map informs users about the estimated performance of various services. Providers can also access u-map to obtain network measurements about their infrastructure and user feedback about their coverage/services

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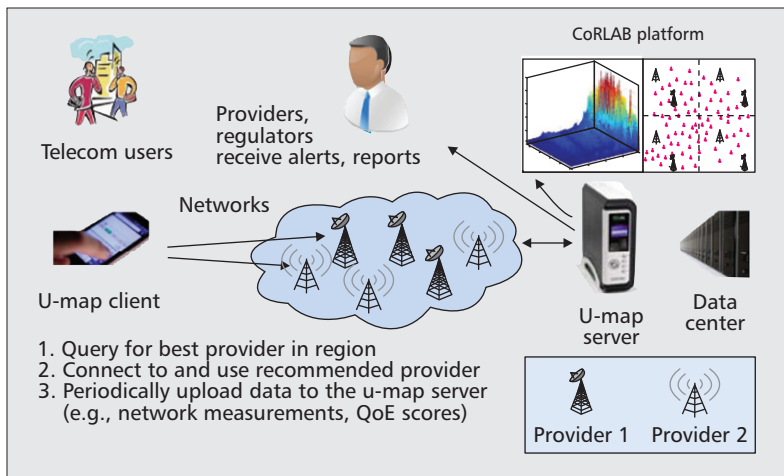
Figure 1. Example of the use of u-map in telecommunication markets: users select the best provider/service, while providers receive reports about potential network failures.

performance to potentially improve/adjust their deployment and services. Thus, u-map can act as an "early-warning" and churn-avoidance mechanism. It also allows them to gain better knowledge about their customers and their QoE criteria, and assess their strategic network planning, pricing decisions, and service deployment strategies at a finer spatial granularity. U-map can also provide feedback about possible compatibility issues of the device, in the context of a service, and their impact on the user experience, allowing the manufacturer, platform/OS developer, and service provider to identify potential problems early and constantly improve their products. Via u-map, regulators can detect whether operators comply to certain specifications. Thus, u-map can become a powerful tool to users, providers, operators, and regulators, introducing a paradigm shift in wireless access markets. Moreover, the team has developed CoRLAB [3, 4], a modeling framework and simulation platform to analyze the evolution of telecommunication markets and services under a diverse set of customer populations and network conditions. In general, the analysis of such markets either adopts agent-based simulations (e.g., [5]) or employs macroscopic models that consider an average behavior of various entities (e.g., [6]). Moreover, such approaches rarely incorporate user-centric data or models in real time. In response, CoRLAB provides a modular *multi-layer* framework, including models at multiple levels of detail: microscopic models that describe each distinct entity (e.g., user) as well as mesoscopic or macroscopic models based on aggregations of entities (e.g., homogeneous user populations). Furthermore, u-map feeds CoRLAB with real-time or semi-real-time data about users and QoE feedback about the received services.

The article is organized as follows. In the following two sections we present the main functionalities of u-map and CoRLAB, respectively. Then we discuss how these systems can be extended for the support of a water distribution network. The final section summarizes our main conclusions and future work plans.

U-MAP

U-map [2] is a recommendation system running on smartphones that follows the client-to-server architecture. In a crowdsourcing manner, it collects various objective and subjective measurements that indicate the performance of a certain service. These measurements are regularly uploaded on a spatio-temporal geo-database and processed by the u-map server. Based on this information, the u-map server can then provide user-centric QoE feedback and recommendations about the availability and performance of the provided services within a region. In addition, CoRLAB obtains these measurements from the u-map server (Fig. 2), and provides various geo-statistics about the evolution and performance of these services. To cope with large user populations, u-map can be developed as a cloud service. The key modules of the u-map architechure include the monitoring, data analytics, QoE modeling, as well as privacy and access control. The following paragraphs discuss them in more detail.

MONITORING

Monitors have been developed for user devices or network infrastructures. For example, monitoring tools may collect various network measurements (e.g., Portolan [7]) or physical-layer information to enable the detection of spectrum availability/usage, whitespace, and interference [8]. The reliability of the measurements and security are significant aspects that need to be addressed. The monitoring tools should not compromise the user privacy. Monitoring on mobile devices needs to also address the energy cost and dependencies on the hardware, while monitoring at the infrastructure, the deployment cost. In the context of u-map, monitoring can be performed at the user mobile devices, as well as at various gateways. The u-map data collection departs from state-of-the-art techniques in the following manner: unlike existing tools, which focus on specific network measurements [7, 8], u-map obtains and correlates a rich set of multi-sourced data with QoE feedback (opinion scores) and geographical information. The collected data can be active or passive cross-layer QoS measurements, user demand statistics, and user preferences. The measurements are uploaded to the u-map server data repository for analysis (e.g., user profiling, QoE inference).

Extensive monitoring and data collection can improve the accuracy of the performance estimates, but also increase the energy consumption and detection delay, as the network interfaces need to monitor the channel over longer time periods and then send this information to the u-map server. U-map can employ advanced signal processing and data mining techniques to determine the appropriate spatio-temporal granularity in the sampling process, and address the accuracy, privacy, and energy constraint trade-offs. The identification of the appropriate parameters that need to be analyzed in order to characterize the specific condition of interest is an important first step in the monitoring process. This determines at which layers and network points and at which
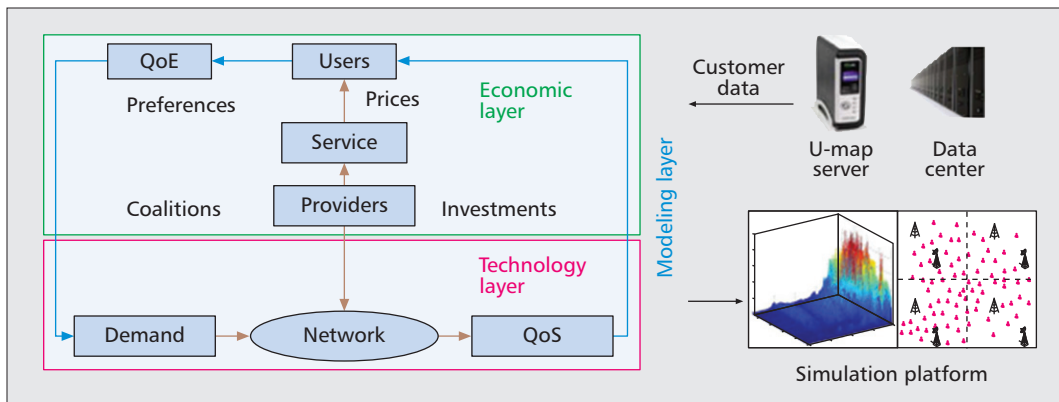
Figure 2. CoRLAB is integrated with u-map. It can model and simulate markets using data provided by u-map.

spatio-temporal granularities the monitoring needs to be performed. The following subsection provides input about these aspects.

DATA ANALYTICS

The user profiling, clustering of user population, QoE modeling, geo-statistics, and warning generation are the primary objectives of the data analytics. Prior to data analysis, a sanitization treatment needs to be performed, since the collected measurements can be noisy, of high dimensionality, erroneous, and sparse. The data sanitization module detects erroneous entries, misconfigured/malicious data sources, and missing values. The statistical analysis method for treating these issues depends on the specific application characteristics, objectives, and requirements.

The user profile "integrates" a number of parameters associated with user preferences, requirements, demand, constraints, and capabilities with respect to services and context. For example, it may include information about the user's willingness to pay, data rate, traffic demand, QoE requirements, feedback consistency, and device characteristics. User profiling can be performed at different levels of detail, which may then impact the computational complexity of the follow-up market analysis. For example, an aggregate-level approach ignores specific individual user aspects and develops general, often less detailed, macroscopic models. On the other hand, a user-centric approach takes into consideration fine-level user information, aiming to form detailed profiles of individual users. A third approach employs clustering algorithms to determine homogeneous user populations and find representative user profiles for each population. Related to user profiling is QoE modeling, which is discussed in more detail in the following subsection.

The spatio-temporal analysis focuses on the geographical and temporal distribution of specific features or metrics, identifying the locality and evolution/spreading of various phenomena. Examples include the analysis of user workload (e.g., amount of traffic, flow arrival process, interactivity model, application, and usage pattern). U-map can provide an early-warning mechanism that appropriately notifies users, pro-

viders, and regulatory authorities about various failures or deficiencies, reducing maintenance costs (e.g., when certain conditions on QoE and traffic load hold). Understanding how user behavior and expectations change depending on the context (e.g., network topology, network conditions, device/technology characteristics, mobility, location, and environment) is challenging, and the performance of empirical-based modeling studies is required.

QoE MODELING

Network benchmarks, such as jitter, latency, and packet loss, have been extensively used to quantify network performance. The evaluation of their impact on the user experience has received a lot of attention from the research community. Especially in the case of high-dimensional measurements, it becomes important to understand which network metrics have a dominant impact on the performance of certain applications, distinguish the conditions that substantially degrade the performance of a given application, and investigate the predictability of these conditions.

QoE is influenced by a diverse set of technical (e.g., QoS and device features), socio-economic (e.g., social network, advertisements, and brand name), human-related (e.g., sentiment and age), business (e.g., pricing, and willingness to pay), and contextual (e.g., time and location) factors [9], some of which are difficult to capture and model. For example, important parameters for VoIP are call setup time (i.e., time from the call initiation request to the beginning of the call), mel-frequency cepstral coefficients (MFCCs) for audio quality measurement, round-trip time (RTT) statistics, packet loss ratio and burstiness, jitter, and number of retransmissions. For video streaming, important parameters include the playback quality (i.e., the bit rate being delivered), startup delay (i.e., time between the user clicks on the play button to the time the video starts playing), buffering ratio (i.e., the percentage of the session duration spent in buffering state) and rate adaptation/ temporal dynamics (i.e., change of the rate during the session), RTT statistics, packet loss ratio, jitter, and number of retransmissions. Parameters to be measured for web browsing include
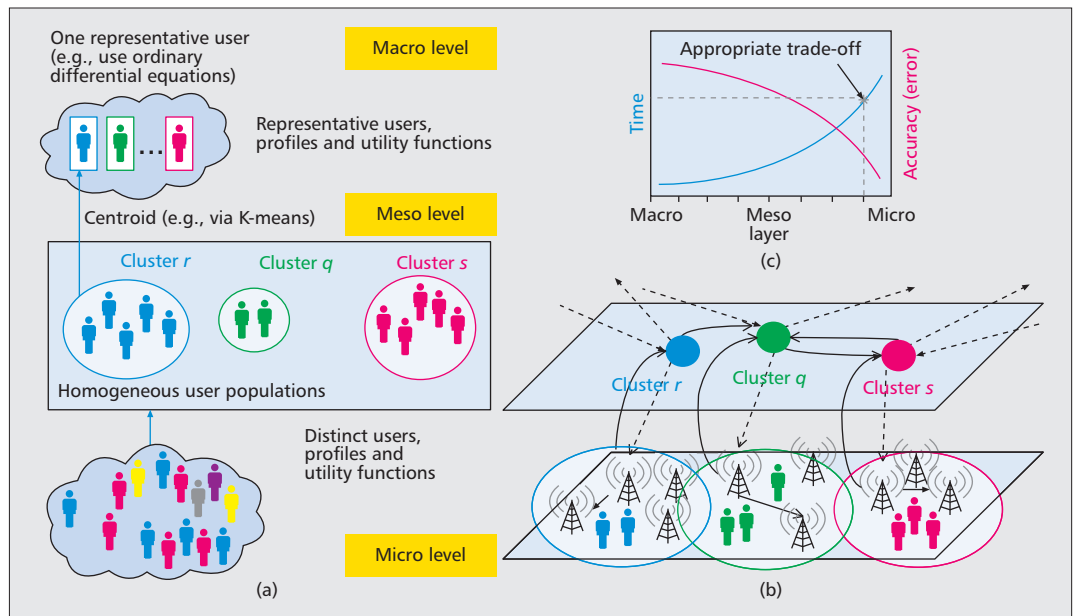
Figure 3. A multi-layer modeling framework has been developed in CoRLAB for the analysis of wireless markets: a) the clusters can be derived based on hierarchical clustering algorithms; b) decomposition methods may enable one to analyze a cluster microscopically and the other clusters macroscopically; c) an example of the accuracy and scalability trade-off. It does not correspond to a specific use case.

page load time (i.e., the difference between the time the URL is requested from the browser and the time the objects are fetched) and lower-layer metrics, such as DNS lookup time, RTT, and TCP retransmission rates. To make the study amenable to theoretical analysis, QoE is usually expressed through simplified utility functions with nice mathematical properties that consider only a subset of these parameters. For instance, E-model [10] and PESQ [11] have been used for modeling the QoE in VoIP. Based on network measurements and subjective feedback collected via u-map, we aim to develop user-centric QoE models that can accurately reflect the user perspective for various services considering different techno-economical factors.

Classification and regression methods based on machine learning, data mining, and statistical modeling algorithms have also been employed for the prediction of QoE [12, 13]. U-map applies a number of state-of-the-art machine learning algorithms, develops and trains models based on the collected network measurements and user feedback, and *dynamically* selects the best one for predicting the QoE in a user-centric manner. A longer-term objective is the inference of QoE without necessarily user intervention or feedback.

PRIVACY AND ACCESS CONTROL

Any time data is shared with a third party, there is a potential for abuse. Therefore, a great deal of effort has been made to design privacy protection techniques for publishing anonymized records. Even though data sharing can be beneficial, users have privacy concerns and value these benefits differently. For example, some may prioritize anonymity, while others may be willing to

share data unconditionally, with most users falling somewhere in between.

To protect user privacy, u-map requires authorization for granting access to the database. The client-to-database connection relies on end-to-end security that protects the integrity and confidentiality of the submitted data by leveraging standard technologies (e.g., public-private key pairs, TLS). For further protection of sensitive information, like user location, access is allowed only to aggregate statistics. Obfuscation approaches (e.g., spatial/temporal cloaking) could also protect user location privacy at the cost of degrading the user experience. For example, if we assume a high level of user privacy, the responses of a location-based service would be inaccurate or untimely. Last but not least, u-map provides a user-centric access control module that allows users to control the information revealed to third parties through a fine-grained discretionary approach. More precisely, access control rules define *who* has access to *what* data, *who* can be a user or another role (e.g., operator, application), and *what* is a query over the data. *Query rewriting* is then applied, "injecting" the access control rules into the request so that the rewritten request filters out the inaccessible data.

DEVELOPMENT

The main functionalities of u-map have been developed, and a pilot testbed has been deployed. Using this testbed, we performed a field study with real users and evaluated the impact of u-map on the user experience in the context of a VoIP service [14]. Based on the collected data, we have also modeled the QoE for VoIP. We plan to extend this study to consider a larger user population.

CoRLAB

Unlike traditional markets, emerging ones are larger (in the number of users and providers), more heterogeneous (in terms of services), and more complex and dynamic (e.g., in the interactions of providers and clients, and their decision making). Modeling such markets is challenging due to a plethora of business, network, and service-related phenomena that manifest at different spatio-temporal scales. Furthermore, the computational and scalability issues when analyzing such markets for long time periods or at a nation-wide level are prominent. The modeling approaches can be classified into two general categories, the microscopic- and macroscopic-level ones. Microscopic-level approaches model each entity, and its interactions with other participating entities, at a fine level of detail. However, due to the high computational complexity, they typically assume a limited number of such entities [5, 15]. On the other hand, macroscopic-level approaches model the *average* behavior of certain types of entities (e.g., user population, service infrastructure) to make the analysis more tractable [6]. However, in many cases they result in inaccuracies and suboptimal performance.

In response to these challenges, CoRLAB, a modeling framework for large-scale diverse and dynamic markets, has been developed. In contrast to the previous approaches, which are either purely microscopic or macroscopic, CoRLAB is a complete multi-layer framework that allows the instantiation of a market at multiple levels of detail. At the microscopic level, the various entities are modeled in fine temporal and spatial detail, while at the macroscopic level, entities are described as a homogeneous population. Between these levels, various mesoscopic levels are defined (Fig. 3) in which entities are grouped in clusters. In a "coarse-grained" procedure, which results in a loss of information in a controlled and hierarchical fashion, the individual entities of the microscopic level (e.g., users) are replaced by clusters with certain attributes, computed based on data mining algorithms. Instead of modeling the decision making of each distinct user, the mesoscopic levels consider a number of user clusters, significantly reducing the computational complexity. Then, based on the requirements of a specific study, the appropriate mesoscopic level that achieves the desired trade-off between accuracy and complexity can be selected (Fig. 3c).

CoRLAB incorporates an economic and a technology layer (Fig. 2). At the economic layer, the decision making of providers and users is modeled using game theory, while at the technology layer, the QoS is estimated using appropriate queuing theoretical models. The QoS metrics and the prices offered by providers are translated through appropriate utility functions to an expression of the user QoE. For the selection of the input parameters of the queuing theoretical models and the parameters of the user utility functions, the contribution of u-map is important since it reflects what happens in actual markets.

The mathematical models in CoRLAB are selected in such a way that they can be studied analytically. However, there are some markets of interest that, due to their inherent features, are analytically intractable. In these cases, CoRLAB employs *empirical game theory*, a recent research direction, to analyze these markets via simulations. The efficiency of this methodology strongly depends on the computational complexity and accuracy of the simulator and the selection of the appropriate mesoscopic level.

CoRLAB has been used to evaluate two scenarios: i) a telecommunication market that offers traditional subscriptions and the "flex service," a novel service that allows users to select their providers dynamically, and ii) a telecommunication market that supports mobile network virtualization. The next sections discuss the outcome of this analysis.

FLEX SERVICE

Traditionally, customers subscribe to specific providers and are served by accessing base stations (BSs) of the network of their provider. Inevitably, subscribers with relatively high usage patterns and data rate requirements are subsidized by those with lower usage and data rates. As wireless network technology advances, a more diverse set of services is made available. To this end, we introduced the paradigm of a *flex user* who is not "locked" to a specific provider, but can dynamically select BSs of different providers based on various criteria, such as network conditions and offered prices [3, 4]. Flex users are flexible in selecting the appropriate provider even on a per-session basis. This flex service paradigm, which has been assumed as a typical access paradigm in wireless LANs, could be a new type of service offered in cellular markets. A similar concept is the "soft" (or virtual) SIM cards. The flex service could be also viewed in the context of a user with multiple available SIM cards. CoRLAB considers a diverse customer population with respect to their demand, their preference on data rate over price, their tolerance for the blocking probabilities of their sessions, and their willingness to pay for certain services. Users can dynamically decide to buy a long-term subscription or become flex users. We analyzed the evolution of a duopoly, focusing on whether flex service can improve the QoS, social welfare, and flexibility, and further enhance the competition among providers. The analysis assumes two infrastructures of time-division multiple access (TDMA)-based BSs and considers the perspective of clients, providers, and regulators.

This work demonstrates the benefits of markets with the flex service paradigm compared to ones with only subscription contracts. The merits are also prominent for specific user populations. A user can select the most suitable product that matches its profile, thus increasing participation in the market. In cases in which the user population is sensitive to blocking probability and data rate, the flex service can improve the revenue of providers. Furthermore, even under different utility functions and price-setting algorithms, several trends persist: for large user populations, the provider with the most resources (i.e., TDMA slots) outperforms in terms of revenue and market share. The reverse trend holds for

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small user populations. This difference between providers is reduced in cost-driven markets compared to QoS-driven ones.

The presence of multiple services may also enhance the competition. Depending on user preference, the flex service may suppress or increase the prices (revenue). In some cases, myopically greedy pricing results in suboptimal performance. In general, the flex service allows finer market segmentation, offering more options to providers and users. Providers can also employ sophisticated pricing schemes that take into consideration the user demand to increase their revenue.

PRICING FOR MOBILE VIRTUAL NETWORK OPERATORS

Wireless communications change in a fast pace. However, not only the networks but also the business models of the communication services over these networks change. For example, network virtualization allows network operators to lease parts of their infrastructure: mobile virtual network operators (MVNOs) do not own a network; instead, they lease resources (e.g., access) in the wholesale market from a mobile network operator (MNO) and resell access services in the retail market. Typically, MVNOs target specific user populations, services, and regions, such as low-willingness-to-pay users (e.g., with low charge-per-month offers), youngsters (e.g., with unlimited SMS, voice minutes over the same network), web users (e.g., with only data offers), ethnic (e.g., with special offers for calls to specific destinations), and roaming users (e.g., with calls, data). Instead of directly competing with MNOs, MVNOs often aim to widen and deepen the market through brand appeal, targeting of niche markets, and alternative distribution channels. The consumer welfare impact of MVNOs is in offering extended and innovative services as opposed to lower prices. CoRLAB analyzed the pricing model of an MVNO in the retail market and the charging scheme of an MNO in the wholesale market. Furthermore, it assessed the impact of knowledge about users on the profits of MVNOs and MNOs. Typically, operators collect such information from market surveys, while CoRLAB employed u-map to obtain this information. The analysis shows that in the absence of capacity constraints, the optimal pricing strategies for both operators depend only on the distribution of users' willingness to pay [16]. The impact of the availability of information on the design of tariff plans was then analyzed via simulations.

A POTENTIAL APPLICATION DOMAIN

Apart from telecommunications, water management is another application domain in which the mechanisms of u-map and CoRLAB could be applied. Fresh water resources are threatened by overexploitation, poor management, ecological degradation, and pollution. Water distribution networks should maintain microbial quality and prevent the growth of pathogenic organisms. In urban environments, such water distribution networks require prevention and monitoring, planning, and management systems to maintain drinking water within acceptable standards.

Sensors measuring water quality in terms of mineral concentration, chlorination level, and bio-agent (e.g., protozoa, E. coli, and salmonella) and noxious substance (e.g., pharmaceuticals) contamination could be installed on various parts of the network (e.g., tanks, large transmission pipe water networks, distribution water networks, and home water networks). Apart from placing sensors and monitoring devices at various points along the path from the main water distribution network to the end users, u-map can empower end users by enabling them to provide real-time feedback about a wide range of factors, such as subjective opinion scores about the quality of water (e.g., unpleasant odor or taste, presence of impurities). This is analogous to our approach to the telecommunication markets, since it enables users to collect network measurements and provide feedback/opinion scores. These measurements would be uploaded on a central server, building a geo-database with combined objective and subjective quality indicators. The aim is to inform users about the water quality in specific regions in order to make optimized decisions about water usage and capacity planning in their infrastructure. Such information can be either automatically transmitted to user smartphones or upon request.

The interested parties (e.g., health centers, hospitals, water distribution operators, governmental/consumer protection organizations) may also build a profile based on their demand and requirements in order to receive personalized notifications. For example, depending on the type of environment (e.g., a residential area, hospital, industrial environment, or farm) and user activity, the quality, demand, and availability requirements may change considerably. Furthermore, different access policies can be applied according to each profile.

The proposed system provides the capability to aggregate measurements about water quality and demand in large spatio-temporal databases, as well as to utilize and correlate a set of multi-sourced data by employing data mining techniques. Based on these data analytics, u-map could provide customized recommendations to users, and predictions or early warnings to various interested parties, and trigger various adaptation mechanisms and events (e.g., change the sampling rate, replace filters). We foresee that adopting u-map for water management purposes may offer great opportunities for early problem identification and alleviation, improving the performance and maintenance process.

CONCLUSION

We have developed u-map, a system running on mobile devices that collects various objective and subjective measurements about the performance of certain services and provides recommendations to users. U-map is integrated with CoRLAB, a multi-layer modeling framework and simulation platform for the analysis of large-scale markets.

CoRLAB has been employed to analyze the flex service in telecommunication markets [3, 4].

Moreover, we have studied pricing strategies in the context of MNOs and MVNOs, and the impact of u-map. Furthermore, we have performed a pilot study and simulation experiments to show the benefits of u-map to wireless users. In the pilot testbed, users may obtain aggregate statistics about the QoE of various services within a specific region and can also query for the best provider according to their profile. We plan to extend the deployment in several cities to evaluate the benefits of u-map.

U-map can be beneficial to network/service operators by providing:
- A better "picture" of their customers, profiles, and user satisfaction in a cost-effective manner (e.g., without questionnaires)
- Real-time geo-statistics and early warning notifications about possible customer problems
- Data to assess their coalitions and roaming agreements with other providers
- Opportunities to extend/improve their services or roll out new ones in a cost-effective manner
- The opportunity to act as a "role model" and satisfy the transparency requirements

Regulators can also audit the providers' conformance to certain regulatory agreements. Via u-map, market transparency is also promoted.

Crowdsourcing systems become useful only after achieving a critical mass of participating members. Sensing on smartphones consumes battery, which might discourage user participation in some scenarios. Similarly, the privacy requirements could also prevent users from participating. Part of our current research is the development of energy-efficient monitoring, effective incentive mechanisms, and business models that encourage participation. Moreover, QoE estimation, with only limited user intervention and training, is of interest. Finally, we plan to extend and generalize CoRLAB and u-map in other application domains, and apply the mechanisms in production networks.

ACKNOWLEDGMENT

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BIOGRAPHIES

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Part of our current research is the development of energy-efficient monitoring, effective incentive mechanisms, and business models that encourage participation. Moreover, the QoE estimation, with only limited user intervention and training, is of interest.