Book Title: Fixed-Mobile Convergence

Chapter X

User-centric Convergence in Telecom Networks

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Abstract

The realization of a user-centric paradigm in future telecommunication networks, which implies free and automatic choice among different available wireless and mobile access networks, will revolutionize the Future Internet. For this innovative concept to materialize, a paradigm shift is required from contract-based mobile service delivery to an open, dynamic service delivery environment. This chapter presents an overview of the user-centric open networking paradigm for future telecommunications and a distributed Quality of Experience framework that enables user-centric, application-specific network selection and handover decisions on the user terminal. Furthermore, a formal modeling of cooperation and resource sharing among operators in this setting is provided, where the QoE framework also acts as an enabler for inter-operator mediation. Specifically, the QoE distribution component is demonstrated to make the truth revealing a dominant strategy for the operators. The interaction between resource sharing operations can be developed with full state information disclosure assumption.

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Introduction

The business models of telecommunication operators have traditionally been based on the concept of the so called “closed garden”: they operate strictly closed infrastructures and base their revenue-generating models on their capacity to retain a set of customers and effectively establish technological and economical barriers to prevent or discourage users from being able to utilize services and resources offered by other operators. After the initial monopoly-like era, an increasing number of (real and virtual) network operators have been observed on the market in most countries. Users benefit from the resulting competition by having a much wider spectrum of choices for more competitive prices.

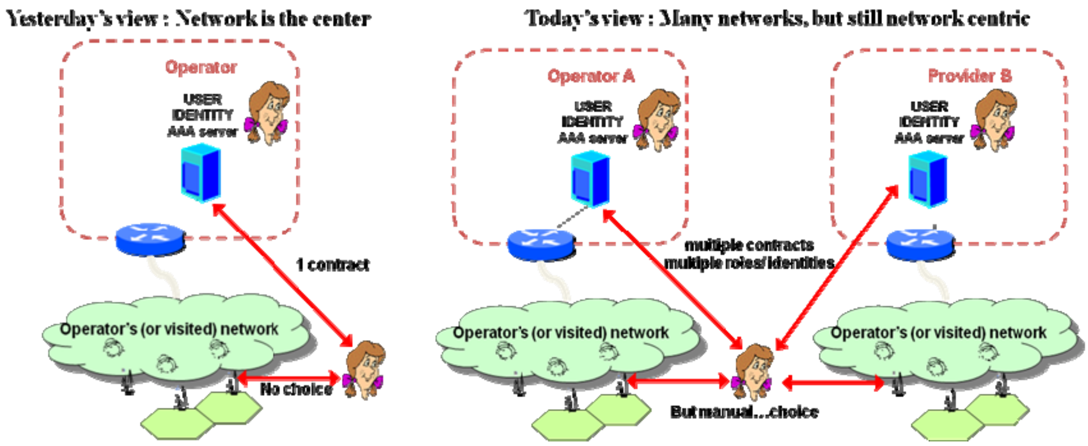

Figure 1. Past and current networking paradigm in the telecom world.

On the other hand, current practices in the telecommunication business still tie the users to a single operator even though the number of players in the market has long been growing. The users tend to manually combine their subscriptions to multiple operators in order to take simultaneous advantage of their different offers that are suited for a variety of services, as illustrated in Figure 1. For example, a user might hold two SIM cards / phones from two distinct operators, one of which provides a flat rate national calling plan while the other provides low cost, high quality international calling with pay as you go option. Extending this example to a case where there is a large number of operators with a multitude of service options and offers in future all-IP telecommunication networks, manual handling of such multi-operator service combinations is clearly tedious and impractical for the user.

User-centric Networking Paradigm

In its most generic sense, the *user-centric* view in telecommunications considers that the users are free from subscription to any one network operator and can instead dynamically choose the most suitable transport infrastructure from the available network providers for their terminal and application requirements [1]. In this approach the decision of interface selection is delegated to the mobile terminal enabling end-users to exploit the best available characteristics of different network technologies and network providers, with the objective of increased satisfaction. The generic term *satisfaction* can be interpreted in different ways, where a natural interpretation would be obtaining a high Quality of Service (QoS) for the lowest price. In order to more accurately express the user experience in telecommunications, the term QoS has been extended to include more subjective and also application-specific measures beyond traditional technical parameters, giving rise to the Quality of Experience (QoE) concept. We will elaborate this in greater detail in the following sections.

The PERIMETER project [2], funded by the European Union under the Framework Program 7 (FP7), has been investigating such user-centric networking paradigm for future telecommunication networks, where the users not only make network selection decisions based on their local QoE evaluation but also share their *QoE evaluations* among each other for increased efficiency and accuracy in network selection, as depicted in Figure 2. This section provides a high-level view of a distributed QoE framework, as introduced by the PERIMETER project, for user-centric network selection and seamless mobility in future telecom networks. The focus is kept on the exploitation of QoE at a conceptual level, while keeping the technical details and implementation issues, e.g. the distributed storage of QoE reports, out of the scope of this section.

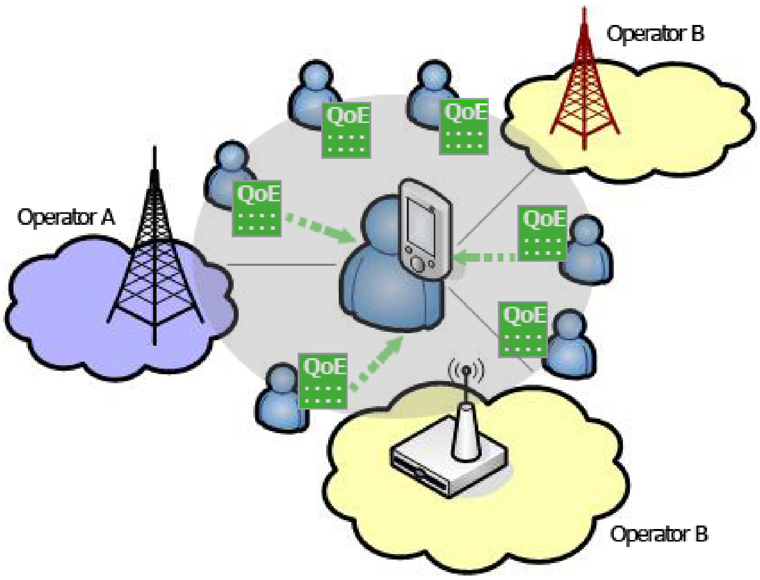

Figure 2. Future user-centric networking paradigm based on a QoE framework.

Quality of Experience

Quality of Experience (QoE) reflects the collective effect of service performances that determines the degree of satisfaction of the end-user, e.g. what user really perceives in terms of usability, accessibility, retainability and integrity of the service. Until now, seamless communications is mostly based on technical network Quality of Service (QoS) parameters, but a true end-user view of QoS is needed to link between QoS and QoE. While existing 3GPP or IETF specifications describe procedures for QoS negotiation, signaling and resource reservation for multimedia applications, such as audio/video communication and multimedia messaging, support for more advanced services, involving interactive applications with diverse and interdependent media components, is not specifically addressed. Such innovative applications, likely to be offered by 3rd party application providers and not the operators, include collaborative virtual environments, smart home applications and networked games. Additionally, although the QoS parameters required by multimedia applications are well known, there is no standard QoS specification enabling to deploy the underlying mechanisms in accordance with the application QoS needs.

For Future Internet to succeed and to gain wide acceptance of innovative applications and service, not only QoS objectives but also QoE have to be met. Perceived quality problems might lead to acceptance problems, especially if money is involved. For this reason, the subjective quality perceived by the user has to be linked to the objective, measurable quality, which is expressed in application and network performance parameters resulting in QoE. Feedback between these entities is a prerequisite for covering the user's perception of quality.

There is no standard yet on evaluating and expressing Quality of Experience (QoE) in a general context. However, there have been recommendation documents or publications that suggest mainly application-specific QoE metrics, objectives, and considerations. Among those, the Technical Report 126 of the DSL Forum (Digital Subscriber Line Forum) is a good source of information on QoE for three basic services composing the so-called triple play services.

Regardless of the specific service context, there are some common factors that have a major influence on the user quality of experience:

- **End user devices** such as an iPhone, Android G1/G2 phone, Blackberry Handset or laptop with a 3G Modem). Various device characteristics, e.g. CPU, memory, screen size, may have a significant influence on the user quality of experience. It is also useful for service providers to know those aspects in order to maximize QoE.

- **The application** running on the terminal is of paramount importance, determining the actual network requirements for a satisfactory QoE level.
- **Radio network** of the operator is usually the bottleneck in terms of capacity, coverage, and mobility aspects, and hence can greatly influence QoE.
- **Operator's application servers** can also have an effect on QoE. Content servers, various gateways, MMSC (Multimedia Messaging Service Center), and streaming servers are typical examples of serving entities. The connection of these servers and their amount on the network might impact QoE as well.
- **Price & billing** is one of the major factors in determining the user satisfaction level for most user groups, therefore could be regarded as part of the QoE specification. High prices for services or billing errors can negatively influence a subscriber's QoE.
- **Network security** has also a big influence on QoE, with the major issues of data hacking attempts or malicious software. QoE can greatly drop when subscribers do not feel that the network is secure.
- **Privacy** is an increasingly common concern in today’s digital society. Users would like to ensure that their identity, communications, and digital actions are well preserved from being exposed or misused by unauthorized parties. Therefore privacy is an important aspect of QoE specification for most services.
- **Core network** components, though not visible directly to subscribers, also have a strong effect on the end-to-end service quality experienced by the user. The core network can affect subscribers’ QoE by affecting connection aspects, such as latency, security, and privacy.

QoE Aggregation and Exploitation

This section presents a partial view on our QoE framework proposed within the PERIMETER project. The aim is not to present a complete picture on the assessment and utilization of QoE, but to set a basis for the second part of the chapter where cooperation and resource sharing among operators is investigated, with this QoE framework acting as an enabler for inter-operator mediation. Figure 3 depicts a local level view of the PERIMETER middleware running on the user terminal, which is responsible for acquiring, processing, and exploiting the QoE related information.

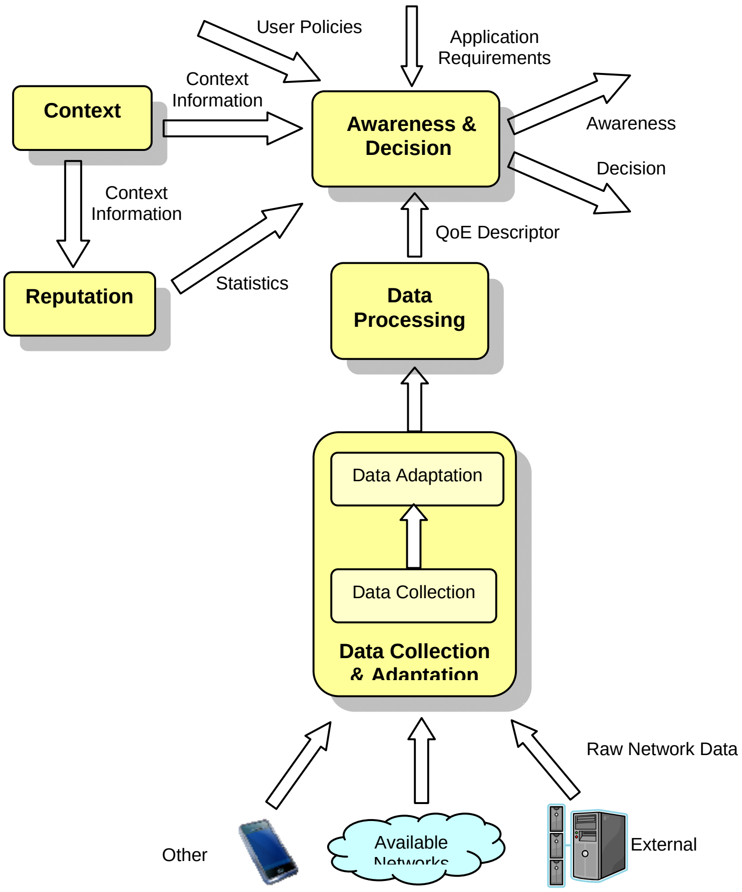

Figure 3. Evaluation and exploitation of the Quality of Experience data in PERIMETER.

Data Network Processor

In order to make user-centric decisions and share user experiences based on the quality of experience, a software entity must first evaluate and quantify QoE for a given set of inputs including the network interface and the application running on the user terminal. Named as the *Data Network Processor* (DNP), this entity is responsible for calculating, from network performance measurements, user's context information and user's feedback, a *QoE descriptor* (QoED). This QoED will be used to take a handover action based on user's policies.

The main responsibility of the DNP is generating QoED reports. Each QoED item is an aggregate and synthetic description of the quality of the user's experience. It consists of a set of key parameters that summarize the quality of service from a user's point of view:

- Mean Opinion Score (MOS) for different types of applications
- Cost rating
- Security rating
- Energy saving issues

Once the QoED is calculated, it is uploaded onto a distributed *knowledge base*, which is a peer to peer storage module running on user terminals and on the so called *support nodes* specifically deployed by the operators with the incentive of obtaining user QoE reports more efficiently. The distributed knowledge base (KB) of QoE reports can then be probed with a QoED query (QoEDq) in order to obtain past QoE reports of other users for decision making, as will be described later in more detail. A QoEDq consists of a set of optional parameters that are used to filter network performance and user's context information stored both locally and globally.

These filters apply to:

- Network connection, to get performance information and QoED items associated to it

- Application information, to get QoED items calculated for applications of the same class
- Geographical location, to get QoED items calculated at the same area
- User’s id, to get QoED items calculated by a certain user

A QoEDq item may contain all or just a reduced set of parameters, allowing a wide variety of queries: QoEDs associated to a certain *provider* or a certain *technology*, etc. The calculated QoED items are mainly utilized by the Decision Maker (DM), which will be described in the following section.

The DNP may generate QoED reports in two different ways: (i) Subscription based reports, where a certain component, which acts as a client from the DNP’s point of view, subscribes to the reception of QoED reports according to a specific QoEDq. (ii) Unsolicited reports, where the DNP takes the initiative and sends a QoED report to all the components that offer a receiving interface for this type of events. The unsolicited reports are triggered by events that are related to an imminent handover action due to a significant change of network conditions, for example, signal loss. In this case, the QoED specifies the network that triggered the event and the actual user’s context description (location, application under use, etc.).

Decision Maker

The Decision Maker (DM) is the entity that makes use of the knowledge gathered by the DNP, user context information, and the preferences entered by the users to take allocation decisions for all the applications running on the terminal. It resides in the Awareness and Decision component of the PERIMETER middleware as shown in Figure 3. The decisions that the DM is responsible for taking are what we call *allocation decisions*, where different applications running on the terminal are allocated to different access networks operated by different network providers. From this perspective the atomic decision is the movement of an application from a certain point of attachment (PoA) to another. This decision is made based on local and remote QoE reports, abstracting the network and subjective user satisfaction, context reports, and user preferences. The main purposes of the decision maker can be listed as follows:

- Take allocation decisions on which operator will be chosen for the applications
- Utilize local and remote QoE reports for the decisions
- Utilize context reports for the decisions
- Utilize user preferences for the decisions
- Infer the failure mode that has led to degradation in the QoE

The novel PERIMETER approach, in which users share their experiences, allows novel decision algorithms to be developed. Within this scope, the DM differentiates itself from the state of the art decision mechanism in the following aspects:

- *Failure Mode Inference*: The DM is able to discern the cause of the problem that has led to the degradation in QoE. The degradation can be due to a problem at the application service provider side, core network side, access network side, or at the air interface. This novelty has two advantages. First of all, it minimizes the number of allocations that require handovers, which puts burden on network components, and degrades the QoE even more for their durations. Secondly, the users are not concerned with the actual cause of degradation in the QoE. They have a holistic view of the application and the service agreement. If an application is not running on an operator network properly, they will most likely blame the network operator, and give a bad MOS input. Thus there is an incentive for the operators to select decision mechanisms that are able to discern the causes of the connection problems. This information can also be used for network optimization purposes.
- *Reasoning*: The fact that users will be exchanging information about subjective measures on

their applications requires a common understanding and agreement on the concepts that make up these subjective measures. This necessitates semantic information to be embedded in the stored information. Reasoning algorithms will be used for taking Failure Mode Inference and taking the appropriate decisions based on the inferred failure mode.

- *Distributed Probing*: Thanks to the PERIMETER middleware, a distributed database of network performance data as experienced from different locations is available. This allows a practical implementation of the distributed probing of the network. This approach is used for Failure Mode Inference at the first stage, but it will be investigated for further utilization purposes that may benefit the network operators as well.

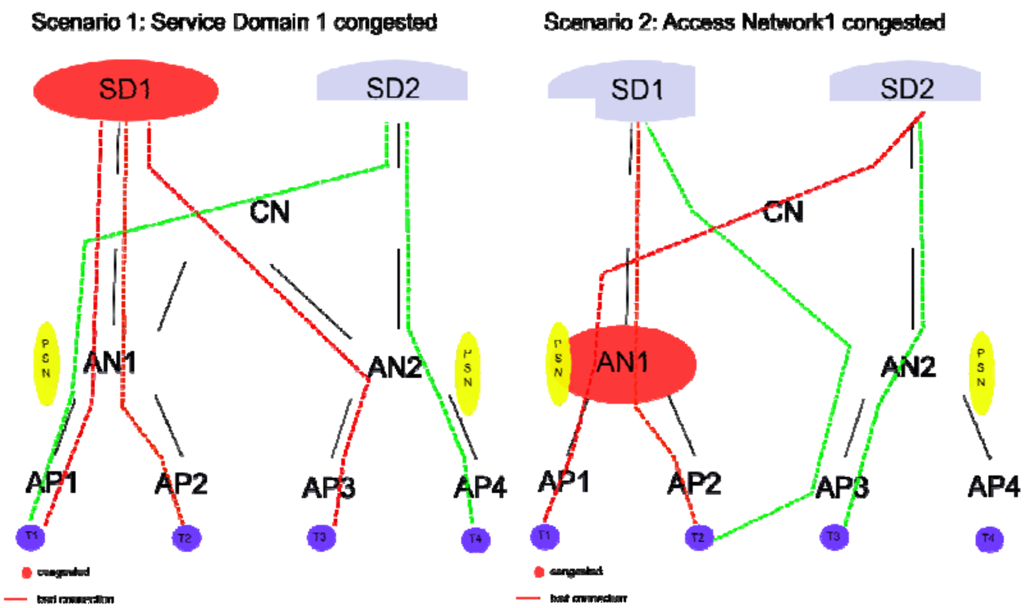

Figure 4. Different modes of failure in a multi-operator, multi-access-technology environment.

The decision maker requests a set of remote QoE reports, which are used to calculate a description map, a mathematical representation of the received reports. These description maps are compared with previously calculated description maps, called *failure profiles,* which are stored in the KB. Each failure profile reflects a specific failure in some part or multiple parts of the network. The comparison of user reports (also called samples) with the failure profiles is based on the assumption that users connected via the same Access Point share the same or at least parts of the route to a certain service and thus experience similar problems accessing their service or using a specific application.

In order to deduce which part of the network is affected by impairments (e.g. congestion), those specific QoE reports must be selected that complement the view on the network. The process of selecting the most useful QoE reports and deducing possible network problems is facilitated by ontological reasoning and rule-based reasoning. The outcome of the reasoning process in the failure mode inference (FMI) component is either that a failure in a specific part of the network could be deduced (in the Access Network (AN), the Core Network (CN) or in the Service Domain (SD)) or the cause for impairments might remain unsolved. This is done by naïve Bayesian Network type of inference. Specifically, summary statistics obtained using the QoE reports generated by different sub groups of users are compared with failure profiles in order to find the source of network failure. Following this procedure, a second inference process called *AllocationDecision* is started to deduce how to react to the deduced network failure. Again remote QoE reports may be requested to provide the inference algorithm with information on network performance, this time focusing on the best allocation of applications considering the result of the previous process.

In user-centric networks, the users' freedom to switch operators in real time and the availability of a distributed knowledge base that stores individual QoE reports will naturally have significant implications on the network operators as well. In the remainder on this chapter, we focus on this perspective and study the interaction among operators in such a setting.

Convergence from the Network Operator Perspective

Telecommunication network management practices are strongly rooted in the monopolistic telecom operators. The liberalization of the operators has only changed the landscape in a way that there were multiple closed operators rather than one closed operator. As a result they are usually centrally managed, poorly integrated with outside components, and strictly isolated from external access. On the other hand the IP world has been about internetworking from its conception on (hence the name IP, Internetworking Protocol). Furthermore the exposure of users to the prolific Internet services means that similar service models will have to be provided by the next generation telecom networks. The clash between these two opposite approaches poses important challenges for network operators. This is due to the fundamental risk associated with their networks turning into mere bit-pipes. In order for future telecom networks to be economically viable, they should provide similar user experience with Internet services, albeit in a more managed and reliable manner.

There lies the grand challenge of the so-called Telco 2.0 operators. The operators have to offer even more data intensive applications on their networks to make their operations profitable. This comes in a time, when the increasing data traffic is starting to hurt user experience, and pose itself as the biggest risk facing the operators [8].

Motivation

The increase in the demand for more networking resources is evident from the discussions above. There are three strategies that the network operators and broadband service providers can follow under these circumstances:

Capacity expansion

Most direct method of combating missing capacity is investing directly to infrastructure. This has been the case for most of the operators who flag shipped the adoption of Apple's iPhone, such as AT&T in the United States. In a press release in March 2009 [9], the company announced that its investment for the state of Illinois alone was $3.3 billion. Industry analysts put the projected capital expenses of the company in the range of $18 billion and discern it as an industry-wide trend. Clearly, this is a brute-force solution to the problem and can only be extended to the point when the investment costs drive access prices beyond market prices. Even if one assumes that the market would adjust all prices accordingly, the emergence of "Greenfield operators" employing new technologies such as WiMAX, or a possible decrease in revenues due to the falling data traffic mean that this strategy is not sustainable.

Employing untapped networking resources

The concept of community communication networks goes bask to the mid 90's [10]. The goal of community networks is reducing the investment costs for the most expensive part of the end-to-end path in communication networks, the access part. Main idea is to combine access points of end users into a single access network, which is then offered to other foreign users in exchange of a fee, or to new members in exchange of access point. Early incarnations of this idea used wired connections such as cable, fiber, and twisted copper networks [11]. With the ubiquity of wireless access networks, realized by the popularity of 802.11-based wireless LANs, idea has experienced a revival. Companies such as FON [12] are already offering commercial community networks, and free communities are burgeoning in European (Berlin [13], Rome[14], Athens[15]) and US (San Francisco [16]) cities employing the 802.11 technology. The 802.16-based solutions for lower population density rural environments are also being proposed in the literature [17], which is yet to become a reality.

The essential role of the community networks from the perspective of mobile fixed convergence is the opening up of last mile wired connectivity to the wireless domain. This new untapped wireless capacity can be used by the network operators to extend their networking resource pool. In fact, the concept of operator assisted community networks has been developed in the literature for the coexistence of community networks with wireless network operators. It has been shown [7] recently that the co-existence of a community network and a licensed operator is viable, under the condition that community network fees are below a threshold value. Such a scenario can be seen as cooperation between the wired ISP that provides the backhaul connectivity to the wireless operator via the proxy of community network.

Mutual Resource Sharing

The final strategy that the operators can follow is to establish strategic partnerships with other operators in order to (i) reduce down the investment costs or (ii) make use of trunking gains in the case of asymmetric service demand profiles. The first option involves sharing varying portions of the end-to-end communication network which we investigate further in the coming sections. However, it is worth noting that the agreements of this sort are off-line in nature that can only be reached after long legal and financial investigations by the negotiating parties.

In the second scenario, an operator gives access to the users of a cooperating operator. This scenario is only viable when the operators are not competing for the same users. For example one operator might concentrate on rural users, who are rarely in the metropolitan area, and the other on urban users. This scenario can also be extended to the case that these operators are virtual operators who are depending on the services of a third operator that provides the infrastructure. This scenario does not require long legal and financial investigations, and is more dynamic in nature. But there are technological and trust related obstacles that need to be addressed before this can be realized.

We believe that the dynamic resource sharing between two licensed or virtual operators and cooperation between a licensed operator and a wireless community network are of similar nature, and face similar obstacles that we want to address. These main challenges are:

- Lack of analytical solutions to model load balancing,
- Information asymmetry and lack of transparency between different operators.

The dynamic nature of the problem requires analytical solutions available to the operator networks to take “cooperate” / “do not cooperate” decisions. An analytical solution has been provided by Tonguz and Yanmaz [18] for the case of load balancing between two access networks of the same operator. However, this formulation necessitates the availability of access network internal information to both of the cooperating parties. This information transparency and symmetry is not applicable to the multi-operator environment. We formulate the problem of modeling resource sharing between access networks with multi-operator assumptions. Furthermore, we utilize the user-centric networking principle presented earlier in this chapter in order to alleviate the information asymmetry and transparency problem. Finally, we propose a game theoretic framework to be employed in user-centric networking scenario, to model the interaction between network operators.

Before presenting the developed framework, we will first compare our dynamic resource sharing proposal to the other resource sharing approaches in the literature, namely the network sharing and spectrum sharing. We then provide a formal problem formulation, and finally present our framework as a possible solution approach.

Relation to the State-of–the-Art

The need for more effective usage of networking resources is self evident. Achieving this by sharing resources has been approached in great detail in the scientific literature and is an industry practice.

Spectrum Sharing

We discern different levels of where the network resource sharing can be realized. In the lowest layer, spectrum sharing and cognitive radio techniques aim at intelligently sharing unused spectrum between users and operators. [23] is an excellent survey on these topics. The main difference to our proposal of sharing resources at the network layer is the fact that both cognitive radio and spectrum sharing require new radio technologies, and are not applicable in the short term.

Network sharing

Network sharing [5][6] is a fairly new industry trend, where operators share varying portions of the access networks to leverage the initial investment and reduce the operation costs of the most expensive part of their networks. Depending on the level of network sharing, the resources shared between operators may involve radio spectrum, backhaul links, and even some network layer links. The main difference to our approach lies in the dynamicity of the sharing agreements.

CRRM

Current wireless telecommunications involve many different radio access technologies, which are specialized for different environments and user contexts. The development as well as the business cycles of these technologies can assure us that they will be available simultaneously for the years to come. *Common Radio Resource Management* (CRRM) [3] is the concept that such multiple radio access technologies (RAT) can be combined in an operator network to diversify the service offer, as well as for making use of trunking gains. Our proposal may be seen as an extension of CRRM methods to multi-operator scenarios.

Problem Formulation

The problem we are addressing is the minimization or avoidance of possible degradation in user perceived quality of experience in an access network as the number of users increases in an open user-centric network environment. In this section, we adhere to the ITU recommendation [19] that relates QoS values to QoE in an exponential manner in order to abstract the QoE assessment level. This relation was defined for voice services, and is being extended for more general data services in the literature [20]. The QoS value we choose is the user experiences in an access network. We therefore make the implicit assumption that the delay in the transport/core network is negligibly small in relation to the access network delay.

The method with which the avoidance or minimization is achieved is by borrowing network layer resources from an access network that belong to another operator (community, virtual or real operator). In a user-centric environment, the operators have to find additional resources, not to degrade the QoE, otherwise the users will be moving away to alternative operators. Therefore the borrowing operator has the incentive to look for additional resources. By making the choice of resource sharing at the network layer, we are making our solution agnostic of the actual mechanism with which resources are shared, which can be realized by allocating explicit spectrum, serving users from the borrowing operator, or by giving backhaul bandwidth.

What would be the incentives for the donor operator to lend some of its resources to the borrower? A quick answer would be that if the donor operator is under-utilized at that particular point of time, then it could increase its utilization to a point where it still can serve its current users, thereby maximizing its revenues. However, the challenge of user centricity comes from the fact that users can instantaneously decide on the operators they choose. Therefore, the donor operator may choose to ignore the borrowing operator, in an attempt to drive the QoE in the borrowing network down, and gain more users. Therefore the dynamics of the resource sharing between two operators become strategy dependent, and not trivial. We aim to bring all the players, the users, the operators; their resource allocation schemes and strategies under a single framework that makes use of queuing networks, game theory, and mechanism design.

The user-centric networking approach makes the aforementioned problem very challenging. However, it is again thanks to this user-centric networking paradigm that this problem is manageable. A key component of the user centric networking is the sharing of user experience through a distributed database, as explained in the first part of this chapter. We assume that this will be an open database, which the users as well as operators will be able to query. We also propose inference methods that can be used by the users, and the operators to overcome the lack of inherent information transparency in the resource sharing problem we described above.

In addition to providing information transparency to the players of this complex resource sharing problem, the distributed user experience database also allows mechanism design principles to be applied to the interaction between the donor and borrowing operators. The key intuition here is the following. If an operator knows that its internal state can be inferred to a certain degree of certainty by the other operator, there is an incentive for both operators to tell the truth about the amount of resources they commit, or request. This property is desirable, as with it we are able to formulate and solve the problem without requiring a neutral third party, for which we have provided a solution in [21].

User-Centric Networking as an Enabler for Network Operator Cooperation

In this section we present the queuing and game theory framework we propose to model the inter-operator resource sharing problem in a user centric network environment.

Stakeholders

The players we consider for modeling the resource sharing interaction are the end users and two operators that serve the users at that particular location. Each of these players has different concerns and incentives for participating in the resource sharing interaction. We explore these individually.

For the initial analysis we assume that there is a single application class that the users use. After an application session is created, the users or the agents on their mobile devices choose the operator that maximizes their QoE. We follow a network-controlled approach to mobility management, which means that users do not change their network after their session has been allocated to a certain operator. It is the responsibility of the operators to handover the user sessions between each other in a seamless manner. The users also publish their QoE reports of the operator to an openly accessible database. By publishing their data, in an anonymous form, they also get access to the data of the other users, which they utilize to take better decisions. Therefore it can be deduced that the users have a strong incentive to publish their data, as long as anonymity is guaranteed. As noted earlier, this database can be implemented in a distributed manner via a peer-to-peer network composed of other end users. In our earlier investigation [24], we have found that the performance of such a mobile peer to peer network can be greatly increased by the introduction of fixed high capacity *support nodes*. We further assume that the network operators will invest in such nodes, in exchange of accessing the anonymous QoE reports. On the other hand, the main concerns of the users are the maximization of their QoE and service continuity.

Our intuition is that the resource sharing is viable, when there is an asymmetry in the utilization of the operators. Therefore we discern a *donor* operator and a *borrowing* operator. The borrower needs additional networking resources in order to keep the QoE of the users it is currently serving. Therefore it has a strong incentive to borrow resources from the donor operator. Its main concern is the continuation of the QoE of the users that would be served by the donor operator. In other words, if donor offers to share a certain amount of resources, the borrower should trust that these resources will be available throughout the sessions of the transferred users, without degradation in their QoE levels. On the other hand, the donor operator has the incentive to lend resources in order to increase its utility. However, it is able to do this only until the additional traffic coming from the borrower starts to reduce the QoE of the users that the donor operator is currently serving. Thus, the main concern of the donor operator is the QoE of the users it is serving. Furthermore, it has to make sure that there is a utilization asymmetry between the operators; otherwise the resource sharing is counter productive, given that the users can choose both operators.

Queuing Model

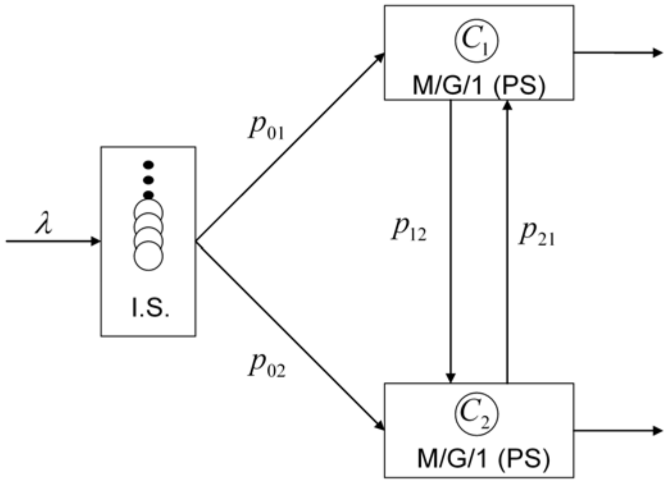

Figure 5. Queuing model for operator interaction

Figure 5 depicts the queuing network model we have used to model the interaction among operators. Queuing networks [25] are generalization of the classical single node queues. In order to define a queuing network, one has to define the node types, the arrival process, and the inter-node traffic matrix, which is composed of probabilities p_{ij} representing the probability that a job leaves node *i* and enters node *j*.

In our model, we chose to use model access networks owned by different operators by a Processor Sharing (PS) node model. PS model has been first proposed by Kleinrock in his seminal paper [27], as an idealization of round-robin style feedback queue. PS is equivalent to a round-robin service discipline, where the time that each job gets during a round is infinitesimally small. The result of this limit is the load dependent behavior of the queue, such that it is as if each user is seeing a queue of capacity *C/k* when there are *k* jobs in a queue of capacity *C*. This generalization is very suitable for wireless networks, where the performance experienced by individual users degrade with the increasing number of users in the wireless network, as long as the technology is interference-limited. Telatar and Gallager [26] were the pioneers of application of PS to wireless multi-access systems, which has been used numerous times since then. Finally, we model the user decision making process with an infinite server queue.

The users choose the operator *i* with probability p_{0i}, which reflects the user decisions. Note that these probabilities are functions of the number of users in different networks, since this number affects the QoE, which is the decision criterion. The probabilities p_{12} and p_{21} are the transfer traffic probabilities. With these definitions we are able to write down the traffic equations:

$$\lambda_1 = \lambda \cdot \frac{p_{01} + p_{02} p_{21}}{1 - p_{12} p_{21}}$$

$$\lambda_2 = \lambda \cdot \frac{p_{02} + p_{01} p_{12}}{1 - p_{12} p_{21}}$$

These represent the effective throughput that each different operator sees, which reduces to

$$\lambda_1 = \lambda \cdot p_{01}$$

$$\lambda_2 = \lambda \cdot (p_{02} + p_{01} p_{12})$$

in our scenario, when 1 is the borrowing operator and the 2 is the donor operator. This reflects the fact that the donor operator is able to increase its utility by allowing more traffic, and borrower is able to keep its input traffic at a level where it can support the QoE demands of its current users. If we call p_{12} the *rate of borrowing* agreed between the operators and denote it by p_B, we are able to represent the additional utility the donor operator gains in terms of p_B, p_{01} and p_{02}. Since there are only two operators in this scenario, the condition $p_{01} + p_{02} = 1$ holds, and hence the donor operator can use p_B as a decision variable in the negotiation with the borrowing operator.

We have to note that we have made a simplifying assumption to come up with these basic traffic equations. The modeling logic behind queuing networks assumes that jobs leave a node after service is completed. However this is not the case for transfer jobs. We can deal with this by assuming that the general distribution for service times includes not only regular jobs, but also shorter length jobs that represent transfer jobs, which leave the borrowing operator after a short stint. We elaborate how we will deal with this assumption as a future work in the last section. The main reason behind the choice of queuing networks and PS discipline is the product form solutions that these type of models have. Generally, a three node network such as ours would be described in an infinite three dimensional state-space, whose solution would require extensive numeric algorithms to run for long time. However this is not possible in the dynamic scenario the user centric networking necessitates. Baskett et al. have shown that the solution for the state probabilities can be expressed as the product of individual state probabilities [28]. For the simple model, we get the following solution for state probabilities $\Pi(k_1, k_2)$, which correspond to the probability that there are k_1 users in operator 1 and k_2 users in operator 2 networks:

$$\Pi(k_1, k_2) = (1-\sigma_1)\cdot{\sigma_1}^{k_1} \times (1-\sigma_2)\cdot{\sigma_2}^{k_2}$$

Where $\sigma_i = \dfrac{\lambda_i(p_B)}{C_i}$. This result is very important, since both of the operators can calculate performance parameters such as blocking probability, throughput and delay, making use of the state probabilities, which is a function of p_B, the transfer probability. This transfer probability can be interpreted as the ratio of requests which enter the borrower operator, but leave from the donor operator. This is the negotiation variable between the operators. As we demonstrate in the next section, the existence of a QoE database that the users and operators can access makes possible a strategy proof negotiation mechanism possible. In such a mechanism fooling of the negotiating partner is not beneficial. We are working on the development of such a mechanism, and therefore present not the mechanism itself, but the procedure to find it.

Trust Establishment in Inter-operator Resource Sharing

We model the interaction between mobile user and network operator as a non-cooperative game. This interaction consists of the users choosing one of the operators, and the operators publishing their spare capacities to the user database. The question here is whether or not it is beneficial to the operator to publish their actual spare capacities, rather than lying. We present here the game-theoretic formulation of this interaction.

Players of the game are network operators and users. Let Σ be the set of operators with elements ω_1 and ω_2. The set of strategies available to the users is to choose ω_1 or ω_2. Payoff of user depending on its strategy is tied to his perceived QoE in the chosen network. This QoE is a function of the number of users in different operator networks. Therefore the user needs this information to maximize his utility. With the aid of QoED database, the user can infer this value with a certain confidence level.

The operators have two choices in their strategy set, i.e. to give the correct or false spare capacity information. Intuitively, when the fact that the users can infer these values is known to the operators, the truth telling strategy dominates.

One can show this dominance by modeling the utility functions of the players appropriately. We model the payoff u_a of users with

$$u_a = \phi e^{-\beta d} + \gamma ,$$

which is the IPQX model for the QoE value associated with average delay *d* [20], which could be obtained utilizing the queuing model. For the operators, the payoff function is clearly the revenue maximization, which can be translated in resource utilization and given by:

$$u_w = \begin{cases} \mu\alpha & if \quad a = \text{associated} \\ \\ 0 & \text{otherwise} \end{cases}$$

where μ represents price per unit bandwidth and α the allocated bandwidth. Since the problem is formulated as a non-cooperative game, one would have to find the Nash Equilibrium strategy profile, and demonstrate that this profile corresponds to a truth telling strategy for both operators. After proving our intuition about the truth revealing capability of the user centric networking, we proceed with modeling the interaction between the donor and borrowing operators.

Let the two network operators be enabled to borrow and donate their resources when needed, thus each operator at a particular time can behave as either resource borrower or resource lender. We also consider that each operator has multiple indivisible items termed as network resource, which may correspond to spectrum, throughput, or set of users. Let $\omega_b \in \Sigma$ represent the borrower operator and $\omega_d \in \Sigma$ represent the lender operator. ω_b knows the amount of resources to be borrowed in order to keep the QoE levels of its users in an acceptable range. It also has a private valuation υ_b of this resource. ω_d is interested in designing a lending mechanism such that it gets the maximum additional utility. In order to achieve this, it requires private information of the borrowing operator, such as amount of spare resources. We have already argued based on intuition that this information would be published by the borrowing operator to the users, which means that this information is not private anymore, but became public. In a similar fashion the amount of spare bandwidth in the donor operator is also public. Based on this public information, it is possible to design a mechanism for finding out the amount of resources to be shared and the payment for these resources. The mechanism would have to be designed to maximize a social choice function, which balances the gain of the borrower and the cost of the donor.

Summary and Future Work

The increasingly dynamic nature of the telecommunications scene is expected to go beyond the technical domain and also cover business models and socioeconomic aspects of telecommunications, eventually giving rise to the user-centric network vision presented in this chapter. There are many challenges, both technical and socioeconomic, that needs to be addressed for this vision to come true, such as the need for a standardized view of QoE among all stakeholders that should act as a common performance and valuation criterion. This chapter has focused on the exploitation of an open QoE knowledge base for resource sharing among network operators. We have presented a queuing network model that was simplified to introduce the main ideas. Specifically, the transfer traffic has not been modeled. It remains as a future work to introduce a separate handover traffic class, and associated traffic class switching probabilities, which become the actual negotiation variable to make our model more realistic. Furthermore, we plan to introduce load dependence of the transition probabilities, which is very important to link the user decisions to the operators' sharing decisions. The idea is that the initial network selection probabilities will favor the operator that has fewer users normalized to the overall capacity. Finally we plan to extend our queuing model to support multiple application classes. Apart from solving the operator user game and formulating the mechanism we will also investigate the range of user distributions over the operators, for which resource sharing makes sense from instantaneous and mean utility maximization. Building up on the intuition that network sharing will be strategically viable in the case of load asymmetry; we will investigate the limits of the level of symmetry. The methodology we will follow for this purpose is the following. Depending on the user distribution between operators, each operator has two choices in their strategy profiles. They can either cooperate, or not cooperate. In the instantaneous utility maximization assumption, the operators compare the instantaneous utility gains from the two strategies, that is they do not consider the future. In the mean utility maximization assumption the operators consider the benefits of altruistic behavior, by taking into account that the other operator might help him in the future, if they happen to be in congestion. This is an application of the well-known iterated game concept.

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