A Multi-Stakeholder Modeling Framework for the Techno-Economic Analysis of Telecommunication Networks

Bernd Simon, Katharina Keller, Artur Sterz, Bernd Freisleben, Oliver Hinz, and Anja Klein

The authors propose a novel multi-stakeholder modeling framework for the techno-economic analysis of telecommunication networks considering the preferences of each stakeholder.

Abstract

Services in telecommunication networks depend on distributed communication, computation, storage, and sensing resources. These resources are owned, operated, and used by different stakeholders. The stakeholders have their own preferences concerning technical or economic attributes associated with investing in, developing, deploying, and using telecommunication technologies. In this work, we propose a novel multi-stakeholder modeling framework for the techno-economic analysis of telecommunication networks considering the preferences of each stakeholder. To analyze autonomous decisions made by each stakeholder, we first present how to identify stakeholders, their utility functions, and how to elicit and integrate their preferences into their utility functions. Furthermore, we highlight important aspects regarding the interactions between stakeholders, such as conflicts of interests, information exchange and information asymmetries, and mutually beneficial interdependencies. Finally, we discuss how to design algorithms to solve multi-stakeholder problems in a given scenario and how to evaluate the results. Using concrete examples from edge computing, mobile crowdsensing, and device-to-device data forwarding, we show three applications of the proposed techno-economic multi-stakeholder modeling framework.

Introduction

Modern telecommunication networks provide distributed communication, computation, storage, and sensing resources owned and used by different stakeholders. Services and technologies in such networks, such as edge computing facilities, mobile crowdsensing, and device-to-device (D2D) data forwarding, involve interactions between multiple stakeholders, characterized by their technical attributes (e.g., data rates and energy consumption) and economic attributes (e.g., capital expenditures [CAPEX] and operational expenditures [OPEX]).

Several research approaches in communication networks focus solely on improving technical attributes (e.g., reducing the energy consumption of edge computing) without considering the economic perspective. Recent works [1] contribute the necessary joint techno-economic perspective (e.g., for future 6G networks). The techno-economic perspective refers to evaluating the system's economic performance and jointly determining the system's technical performance (e.g., wireless coverage or energy consumption). However, these works are limited to single stakeholder perspectives, and techno-economic analyses of the interaction of multiple stakeholders are scarce [2]. We argue that the single stakeholder perspective should be extended to a techno-economic multi-stakeholder view, considering the preferences of all stakeholders. Modeling the different stakeholders is an important part of successful project planning [3]. In particular, the conflicting interests and constraints imposed by the different stakeholders have to be considered. As far as we know, the previous literature has not considered a techno-economic multi-stakeholder view of telecommunications networks.

In a multi-stakeholder scenario, there are open questions from different perspectives. From the perspective of researchers, the following questions, among others, are relevant:

- How should we model a telecommunication network including multiple stakeholders with their technical and economic aspects and preferences in a single joint model?
- How can we assess the preferences regarding economic and technical quantities realistically?
- How should we design algorithms for decision making that consider the stakeholders' different preferences?

From the perspective of companies, questions about their own technical and economic attributes and the preferences of other stakeholders are important, including:

- What are the companies' preferences and requirements concerning technical and economic attributes for deploying a novel technology?
- How can modelers elicit relevant preferences of customers and providers?
- What information should be exchanged with other stakeholders to improve decisions without revealing private information?
- How should companies design effective incentives for other stakeholders?

From the perspective of regulators, the following questions, among others, arise:

- In which cases is the regulator's influence necessary because autonomous stakeholders' decisions lead to undesirable outcomes?
- What incentive structures align the individual

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Bernd Simon and Anja Klein are with the Technical University of Darmstadt, Germany; Katharina Keller and Oliver Hinz are with Goethe University Frankfurt, Germany; Artur Sterz and Bernd Freisleben are with the University of Marburg, Germany.

utility functions with a global utility so that cooperation between stakeholders is stimulated?

To answer such questions, methods to assess the stakeholders' technical and economic considerations, including the elicitation of preferences, are required. In this work, we present a multi-stakeholder modeling framework for techno-economic analyses. Instead of arbitrarily combining economic and technical attributes (e.g., energy consumption and OPEX [4]) in a utility function, we discuss approaches for evaluating each stakeholder's technical and economic attributes, preferences, and utility functions by combining technical analysis and market research methods. We discuss various concepts to introduce the multi-stakeholder perspective into all elements of the techno-economic analysis, e.g., to evaluate economic feasibility, guide research and development, and quantify uncertainty and risk of novel services and technologies.

This article is organized as follows. We introduce the stakeholder concept. We present the stakeholders' utility functions and illustrate how the stakeholder preferences can be elicited. We discuss different aspects of stakeholder interactions. We show how to design algorithms to perform a multi-stakeholder techno-economic analysis. We present three applications of the proposed modeling framework. Finally, we conclude this article.

Stakeholder Identification

The first step in a techno-economic multi-stakeholder modeling framework is to identify all stakeholders relevant to the scenario considered and the problem investigated. Stakeholders are autonomous decision makers who can influence or are influenced by the decisions of other stakeholders [5]. Furthermore, each stakeholder maximizes its techno-economic utility function, which incorporates the cost-benefit trade-offs and the stakeholder preferences. Any problem to be analyzed in telecommunication networks first requires identifying all relevant stakeholders.

To give an example of stakeholder identification, we consider a possible scenario of mobile service delivery in which users access different services in the network. Depending on the problem being analyzed, different stakeholders may be relevant. For example, in mobile service delivery using edge computing, three stakeholders can be identified [6], as shown in Fig. 1: an infrastructure provider (IP) offering edge computing facilities for lease, a service provider (SP) deploying services on the IP's infrastructure, and users using the service. The problem analyzed in this scenario could be the allocation of services on different edge computing facilities to reduce the OPEX of the SPs while reaching an agreement with the IP. However, in the same scenario but with different problem statements, the stakeholders could be others, such as mobile network operators (MNOs), cloud providers, or content delivery network (CDN) providers. SPs offer services to users based on communication, computation, sensing, and storage resources, such as mobile augmented reality (AR) or virtual reality (VR) games and video streaming, or data from mobile crowdsensing (e.g., traffic information).

However, a distinction between the three stakeholders (SP, IP, and user) does not fit all scenarios. For example, micro-operators targeting specific customers from different market segments require greater flexibility in modeling the stakeholders [7]. Furthermore, ongoing vertical integration (e.g., due to SPs' large investments in their infrastructure) complicates the distinction between SP and IP. The identified stakeholders might also be modeled to a varying degree of abstraction. To be more precise, specific companies may be modeled with their dedicated individual utility functions and preferences. However, more abstract stakeholders can also be modeled based on generalizations containing multiple stakeholders' essential features with a common function in the corresponding scenario. An example of such a stakeholder could be a generalized IP (e.g., using models of edge computing and cloud providers depending on the problem).

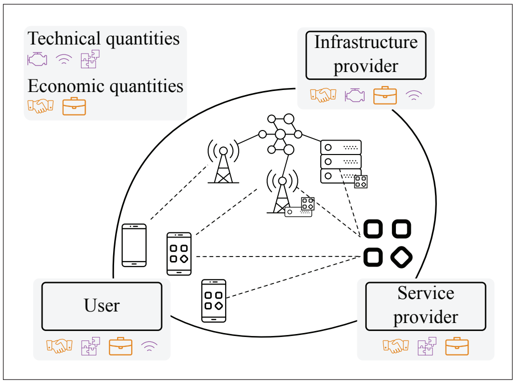

FIGURE 1. Exemplary stakeholders in a mobile services delivery network.

The first step in a techno-economic multi-stakeholder modeling framework is to identify all stakeholders relevant for the scenario considered and the problem investigated. Stakeholders are autonomous decision makers who can influence or are influenced by the decisions of other stakeholders.

So far, stakeholders have had in common that they either offer something (e.g., infrastructure or services) or have a demand (e.g., consumers of a service or users of network infrastructure). However, another class of stakeholders neither provides nor requires resources, such as regulators or academics. Instead, these stakeholders evaluate the performance using a global utility (e.g. social welfare) and regulate the behavior of the other stakeholders, for example, by incentives.

This global utility function contains technical aspects of the entire network, such as system throughput, coverage, and energy consumption, as well as economic aspects, such as the overall economic welfare of the system.

Techno-Economic Utility Functions and Preferences

Utility Functions

When investigating, developing, deploying, or using novel technologies, stakeholders have to make decisions. In the presented example of mobile service delivery, a decision could be (e.g., for the IP) where to deploy which hardware; the SP's decision could be what resources are necessary and appropriate to provide services; and for users, which services should be used. For decision making, technical quantities play a role, for example, the network coverage from the perspective of the IP, the service availability from the perspective of the SP, and the quality of service (QoS) for the users. Additionally, each stakeholder has economic quantities, such as CAPEX and OPEX of IPs and SPs, or the service cost of users. This results in techno-economic considerations for each stakeholder: for the IP to balance coverage, CAPEX, and OPEX, for the SP to balance service availability and resource cost, and for users to balance energy consumption and

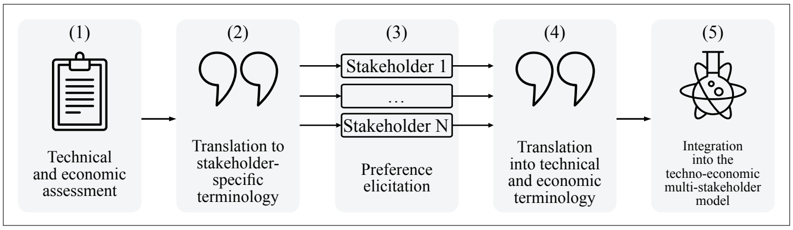

FIGURE 2. Process model to elicit and integrate the stakeholders' preferences into the techno-economic model.

service usage. Since these technical and economic quantities influence each other, the decision making is very complex due to many alternatives in the decision process. To include multiple criteria in decision-making, multi-criteria decision making (MCDM) research offers several approaches [8].

The approach we propose is to construct a single utility function by weighting each of the technical and economic quantities and weighting them according to stakeholder preferences. We focus on the approach to construct a single local utility by weighting each of the technical and economic quantities, where the weights are given by the stakeholders' preferences.

Stakeholder Preferences

Process Model to Elicit and Integrate the Stakeholders' Preferences into the Techno-Economic Model

In this section, we present a process model to analyze the preferences of each stakeholder in a given scenario. Figure 2 illustrates the general procedure. First, we (1) assess the technical and economic parameters and (2) translate them to stakeholder-specific terminology (i.e., terms that are understandable to the respective addressee). For example, different terms and explanations should be used in user studies for less tech-savvy respondents than when interviewing a service provider's technical teams, since the latter are familiar with the technical basics. Then we (3) elicit the preferences using appropriate qualitative or quantitative market research methods. After preference elicitation, we (4) translate the results back into technical and economic terminology. Finally, we develop (5) a multi-stakeholder model that incorporates these realistic preferences.

If we decide to conduct *qualitative research* in step (3), we can use, for example, expert interviews to investigate complex systems in their entirety. In particular, we can employ these methods to identify theories about how technical and economic quantities are integrated into the local utility functions. The process model enables us to analyze the preferences of SPs and IPs, especially if the number of respondents is insufficient to conduct quantitative research. Depending on the target stakeholder and corresponding respondents, the attributes under consideration must first be translated into stakeholder-specific terminology in the preceding step (2).

One possible method for conducting qualitative research is interviews, which can be evaluated using grounded theory, for example. When conducting an interview with experts in the technical domain, we formulate questions about use cases, implementations, or technical requirements. Questions about the potential business model, CAPEX, OPEX, or risk affinity are suitable for experts in the economic field. Grounded theory aims to develop theories to explain stakeholder behavior empirically, for example, by collecting data in the form of interviews and the subsequent analysis. Using qualitative research, we can determine the relevant technical and economic quantities for each stakeholder.

To obtain realistic preferences of stakeholders in the analyzed scenario in step (3), we can also use *quantitative research* methods, such as surveys, which allow us to investigate the relationships between different technical and economic quantities and conditions. We can use these methods to analyze user preferences, determine importance weights of technical and economic quantities, and estimate participation rates in technologies where users as decision makers play an important role. To elicit the preferences (3), choice-based conjoint analysis (CBC) can be used. It is a powerful method used in behavioral sciences and market research. Based on the trade-off decisions, the weights for the individual technical or economic quantities can be estimated. Conclusions can be drawn about the attractiveness of individual technology attributes, providing valuable insights into user preferences. Using quantitative research, we can determine the exact formulation of the stakeholder's utility function.

Interaction between Stakeholders

Conflicts of Interests

In multi-stakeholder approaches, conflicts of interest between stakeholders are likely, as suggested by research in the area of project planning [9]. The simplest form of such a conflict of interest could be, say, two stakeholders negotiating a price for a resource, such as using cloud resources. Here, both stakeholders have an apparent conflict of interest: While the SP wants to pay/negotiate a price as low as possible for the use of the cloud to minimize its OPEX, the cloud provider wants to maximize its profit and thus sets the price of the cloud resources as high as possible. The stakeholders' intentions can also influence whether they are interested in a joint solution and cooperate in the search for a solution or if they do not cooperate or even have a competitive relationship. In the latter case, however, additional costs may arise for all stakeholders involved. These arise either from the need for a third, independent party, such as brokers, to help find a solution or from decentralized approaches that may not lead to an optimal outcome. The difference between an optimal and the found solution must be considered as an additional cost in the utility of both stakeholders.

Information Exchange and Asymmetries

In most scenarios, stakeholders do not have complete information about other stakeholders because they keep some information private that they do not want to share [10] (e.g., due to the wish to retain bargaining power) or cannot share (e.g., due to technical limitations). For example, SPs and IPs in resource provisioning scenarios have private information about their business models (e.g., their cost structure), and users might not want to share their location. Therefore, each stakeholder must make decisions based on partial, missing, or inaccurate information about

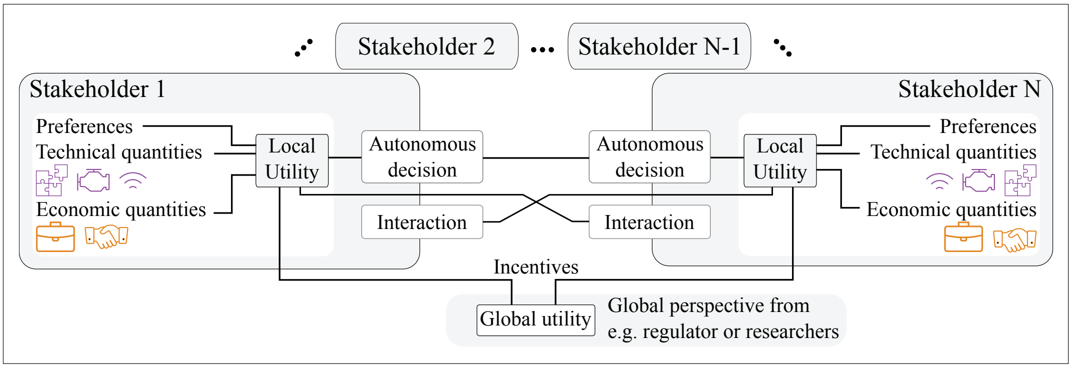

FIGURE 3. A techno-economic, multi-stakeholder model with stakeholder preferences.

Although stakeholders in telecommunication networks often have to deal with conflicting interests and information asymmetries, there are also positive influences between stakeholders.

other stakeholders. In addition, stakeholders have access to different sources of information, which leads to information asymmetries. A key question in this context is which and how much information each stakeholder should share to achieve better results when interacting with other stakeholders. When assessing what amount of shared information is optimal, we propose analyzing the impact of sharing each quantity or accumulated quantities of the local utility. Sharing partial information might result in better results, such as higher cost reduction, but might also result in a less powerful bargaining position. The consideration of which information to share and which to keep private must be made separately for each scenario to achieve the best possible result.

Mutually Beneficial Interdependencies

Although stakeholders in telecommunication networks often have to deal with conflicting interests and information asymmetries, there are also positive influences between stakeholders. For example, suppose a network provider improves its network capabilities as the result of a techno-economic analysis conducted with an SP. In that case, other SPs will likely benefit from the resulting better network capabilities. In the other way, novel services will also attract new users, allowing network operators to have new opportunities and options in future techno-economic analyses. Such effects are called positive externalities or spillovers. Mutually beneficial interdependencies can be handled in the proposed modelling framework by integrating additional terms in the local utility functions which depend on the decision of other stakeholders.

Algorithm Design and Analysis

Based on the identified stakeholders, including their utility, preferences, and interactions, the next step is to formulate optimization problems and design algorithms that solve the problem statement of the given techno-economic analysis in the scenario. As discussed earlier, each stakeholder has a different optimization goal. Methods from game theory such as the Nash bargaining solution, contract theory, or transaction cost theory can be used to optimize strategies in scenarios with multiple selfish stakeholders. Integrating machine learning approaches enables stakeholders to optimize their utility in the given scenario by learning from past decisions, interactions, or information. For example, in the mobile service delivery scenario, users' behavior could be learned to find optimal edge computing locations. For the evaluation of the performance of the derived algorithms, stakeholders can apply various methods. For example, they can use analytical evaluations to measure technical improvements or infer users' subjective improvements. Moreover, statistical simulations can be used, such as Monte Carlo simulations or Latin Hypercube sampling.

Regulators may aim for social welfare as a regulatory goal, in addition to trade-offs between different forms of efficiency (e.g., allocative efficiency) and distribution aspects (which stakeholder gets what or how much and from whom). Regulators impose bodies of rules that stimulate compatibility by giving different types of incentives (e.g., tax breaks, subsidies) or charging fines. The goal of these incentives or fines is to achieve desirable market outcomes and mitigate market failures. Regulators need to assess their impact on the incurred cost for the stakeholders and the resulting benefits, where the area of regulatory impact assessment offers a variety of approaches [11].

Figure 3 visualizes the resulting model, which includes the identified stakeholders, their local utilities containing their preferences, and the technical and economic quantities. It also presents the interactions between the stakeholders and the regulators' perspective earlier, and autonomous decisions based on algorithms.

Applying the Modeling Framework

In this section, we present three examples where we applied the proposed techno-economic modeling framework to show its feasibility. These applications are a *service placement* application in an edge computing scenario [12], a *crowdsensing* application [13], and a D2D data forwarding [14] application. We applied appropriate components in each example to model the scenario and solve the problem statements.

The *service placement* application involves the following stakeholders: an IP offering cloudlets (i.e., edge computing resources for rent) and an SP aiming to place its service on these cloudlets. These stakeholders are companies that seek to reduce their OPEX. In this scenario, cloudlets offer the potential to reduce the OPEX by placing service on cloudlets with high user utilization. The stakeholders' utility functions contain costs for data transfer, processing, hardware provisioning, and maintenance. To place the SP's service on the IP's hardware, both stakeholders have to agree on the locations and the payment. For this purpose, both stakeholders can estimate their technical quantities (i.e., resource demand) based on their own historical data. However, the SP's historical data contains more information about its users, resulting in an information asymmetry between the stakeholders. Furthermore, both have only private information about their economic quantities. Therefore, a game-theoretic approach called the Nash bargaining solution (NBS) is an appropriate way to achieve an agreement about using cloudlets. To incorporate the identified incomplete information, the stakeholders can use publicly available information, such as competitors' price lists, and adjust the NBS accordingly. To reduce the information asymmetry related to the service's users, both stakeholders can either predict the service usage themselves or share this information to achieve better results in terms of OPEX reduction.

The stakeholders involved in the exemplary crowdsensing application are a crowdsensing platform and the users. The platform receives data from its users, who collect and upload the data. Interactions between the platform and its users primarily focus on incentivizing users to contribute their data. Users have preferences regarding the incentive mechanism, such as whether they want to get micropayments or data from the crowdsensing platform. Therefore, the platform's challenges are incentivizing users, assigning tasks according to user preferences, and allocating limited communication resources. Thus, we modeled an efficient algorithm that uses a hierarchical structure, decomposing the assignment game into multiple smaller instances with fewer decision makers in each instance.

For the *D2D* application, the stakeholders are an IP that aims to utilize the data forwarding capabilities of its users, as well as the customers of that IP. To elicit the user preferences in the D2D application, we identified the following criteria for the user study: throughput, latency, amount of transferred data, consumed energy, and relationship to the receiving user. We translated these technical terms into terminology that the users understand. Throughput and latency were translated to service type and the amount of transferred data to service duration. Consumed energy became the remaining battery level, and the relationship to the receiving user was not translated but used verbatim. The results of the user study using a conjoint analysis show that the relationship to the receiver is by far the most important attribute.Specifically, close relationships, such as families/partners and friends, positively influence the decision to participate in D2D communication as a forwarder. The resulting utility function is a linear combination of the technical and economic attributes, where the users' preferences provide the importance weights for each of the technical and economic attributes. The resulting utility function can be used to analyze the participation rate of users. These examples show that the proposed modeling framework allows us to analyze a broad range of problem formulations in different scenarios.

Conclusion and Outlook

In this article, we propose a modeling framework that considers multiple stakeholders in telecommunication networks with their individual techno-economic perspectives, preferences, and related utility functions for developing, deploying, and using novel telecommunication technologies. This work provides an overview of the fundamental tools and terminology for techno-economic multi-stakeholder analyses. Future research activities include integrating transaction and coordination costs into the multi-stakeholder model.

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Biographies

Bernd Simon [StM] (b.simon@nt.tu-darmstadt.de) is pursuing a Ph.D. in electrical engineering at TU Darmstadt, Germany, in the Communications Engineering Lab. His research interests include the application of game theory in wireless networks.

Katharina Keller (kakeller@wiwi.uni-frankfurt.de) is a postdoctoral researcher in the Chair of Information Systems and Information Management at Goethe University Frankfurt. Her research interests include modeling and understanding user preferences for innovative technologies.

Artur Sterz (sterz@informatik.uni-marburg.de) is a postdoctoral researcher in the Department of Mathematics and Computer Science at Philipps-Universität Marburg. His research focuses on wireless communication in mobile networks.

Bernd Freisleben [M] (freisleb@informatik.uni-marburg.de) is a full professor of computer science at the University of Marburg, Germany. His research interests include distributed systems, mobile computing, and networked applications.

Oliver Hinz (ohinz@wiwi.uni-frankfurt.de) is a full professor of information systems and information management at Goethe University Frankfurt. He is interested in research at the intersection of technology and markets.

Anja Klein [M] (a.klein@nt.tu-darmstadt.de) is a full professor at the TU Darmstadt, Germany, heading the Communications Engineering Lab. Her research interests lie in resource management in wireless communications.