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Insights in the cost of continuous broadband Internet on trains for multi-service deployments by multiple actors with resource sharing

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Abstract

The economic viability of broadband Internet services on trains has always been proved difficult, mainly due to a high investment cost and low willingness to pay by train passengers, but also due to unused opportunities such as non-passenger services (e.g. train performance monitoring, crew services) and optimization of the resources consumed to offer Internet services. Evaluating opportunities to improve the return on investment is therefore essential towards profitability of the business case. By efficiently sharing resources amongst services, costs can be pooled over several services in order to reduce the investment cost per service. Current techno-economic evaluation models are hard to apply to cost allocation in a multi-service deployment with multiple actors and resource sharing. We therefore propose a new evaluation model and apply it to a deployment of Internet services on trains. We start with a detailed analysis of the technical architecture required to provide Internet access on trains. For each component, we investigate the impact by the different services on resource consumption. The proposed techno-economic evaluation model is then applied in order to calculate the total cost and allocate the used and unused resources to the appropriate services. In a final step, we calculate the business case for each stakeholder involved in the offering of these services. This paper details the proposed model and reports on our findings for a multi-service deployment by multiple actors. Results show important benefits for the case that considers the application of resource sharing in a multi-service, multi-actor scenario and the proposed model produces insights in the contributors to the cost per service and the unused amount of a resource. In addition, ex-ante insights in the cost flows per involved actor are obtained and the model can easily be extended to include revenue flows to evaluate the profitability per actor. As a consequence, the proposed model should be considered to support and stimulate upcoming multi-actor investment decisions for Internet-based multi-service offerings on-board trains with resource sharing.

Keywords: Internet; Rail; Techno-economic analysis; Multi-service; Multi-actor; Resource sharing; Network costs; Service costs

Introduction

Motivation

People expect to be able to get on the Internet independent of their location, as such Internet access is increasingly available on trains. In 2005, Thalys, a European train operating company (TOC) operating high-speed trains between Paris, Brussels, Amsterdam and Cologne, started with an offering of on-board broadband Internet. Nederlandse Spoorwegen, a Dutch government-owned TOC, started tests with on-board broadband Internet in 2005. In 2011, the service has been rolled out in the 100th train. Nederlandse Spoorwegen claims that by 2013, all of its trains will be equipped with Wi-Fi hotspots. In 2011, the Bejing-Shanghai high-speed railway started the rollout of high-speed Internet for commuters, and in 2013, Indian Railways has launched a pilot project to install a free Wi-Fi service in passenger trains in the country. Travelers taking the Eurostar will be able to use Wi-Fi to surf the Internet

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on-board from early 2013. Many other roll-outs have been completed or are being planned.

According to [1], providing Internet access to passengers on-board trains makes good business sense: Internet access for passengers can provide a revenue stream for the train company while attracting more travelers. But, previous techno-economic investigation shows that solely providing support for Internet on-board for travelers will have a negative return on investment [2]. In general, the economic viability of broadband Internet services on trains has been proven difficult mainly due to a high investment cost and low willingness to pay because Internet is more and more considered as an expected amenity [3] but also due to unused opportunities such as offering other services and optimization of resource consumption. Evaluating opportunities to improve the return on investment is therefore essential towards profitability of the business case.

Next to passenger Internet, service operators show interest in offering services on trains such as passenger comfort services, operational applications and safety and security applications. These services use many of the same resources that are deployed for providing Internet for passengers. By efficiently sharing resources amongst services, this cost can be pooled over several services in order to reduce total cost of operation per service.

In this article, we provide an assessment of the economic gains in terms of service-related cost savings, provided by the joint deployment of several services against a deployment of a single service. This assessment is obtained by combining the technical architecture for train-to-wayside communication with Quality of Service (QoS) over heterogeneous wireless networks from [4] and a techno-economic model based on [5], whose cost model comes from industry data. Savings by resource sharing are estimated and the costs are distributed between actors, what is critical information for the business models of the involved actors.

Contribution

The purpose of this article is evaluating the economic gain provided by the joint deployment of several Internet services on trains. To this end, the technical architecture for train-to-wayside communication and a techno-economic model have been combined, as described in the sequel, to dimension the on-board, train-to-wayside and wayside resources. The whole dimensioning process allows us to assess the total cost that is required to offer the services. Two service deployments are compared: a stand-alone, free Wi-Fi service for passengers and a free Wi-Fi service deployed in conjunction with a paid video-on-demand service and a crew communication service.

Under this framework, a comparison in service-related cost savings provided by a multi-service deployment is presented. For each component, we investigate the impact by the different services on resource consumption. An activity based cost methodology is then applied in order to allocate the used and unused resources to the appropriate services. In a final step, we calculate the business case for each stakeholder involved in the offering of these services.

Outline of the article

This article is organized as follows: The next section introduces the technical architecture for train-to-wayside communication with QoS over heterogeneous wireless networks, which is input for the techno-economic model. In the ‘Techno-economic model’ section, the techno-economic model and the methodology used to evaluate the service-related costs are presented, as well as the main assumptions in terms of market parameters, network architecture, cost assesment and value network. The ‘Main results and discussion’ section presents the main results and the discussion about the economic benefits provided by the joint deployment of Internet services on trains. ‘Conclusions’ section concludes the article and points at possible future work.

Technical solutions to providing Internet services on trains

Several network architectures are possible to provide wireless train-to-wayside Internet services. For our study, the train-to-wayside architecture described in [4] is used. This architecture can handle QoS requirements from different services over heterogeneous wireless networks.

In Figure 1, a global overview of the T2W communication topology is depicted. Multiple services are running on devices on-board the train or on the wayside at the integrator or at a third party (e.g. a service provider) connected to the Internet. The generated data needs to reach its destination on the wayside or on-board. Therefore, the data travels from the train over a wireless link to the network of a network operator. From the network operator, data flows over a leased line or a secure tunnel over the Internet core network from the network operator to the network of the integrator. From the integrator, the data is further routed to the service provider. The same route, but in reverse direction is used for data that flows from the wayside to the train.

To establish communication, each consist, which is a fixed combination of cars of a train, has a mobile gateway server on-board while the integrator hosts a wayside gateway server at the wayside. The mobile gateway is the on-board standard gateway for all outgoing traffic, originating from the train, while the wayside gateway server is the standard gateway for all traffic towards the trains, originating from the wayside.

The on-board devices simply connect to a local access point on-board the train and are unaware of the fact

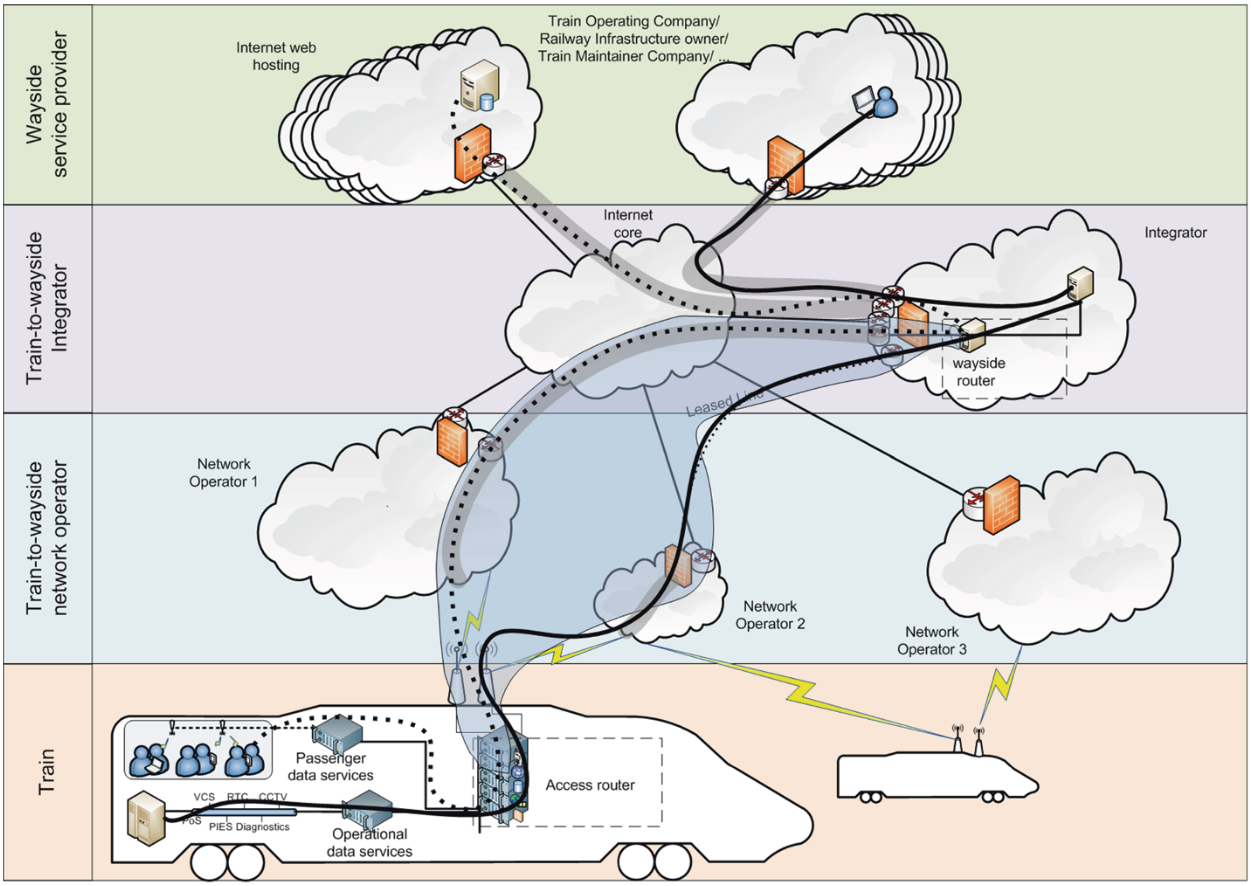

Figure 1 Network architecture to provide Internet services on-board trains. A typical passenger data service flow is depicted by a dotted line, an operational data service flow in a solid line. The transparent envelope symbolizes the hiding of the Train-Integrator tunnels from the outside. There are three types of network operators that can be used to obtain the wireless link: a satellite operator, an existing mobile network operator and deploying and operating a dedicated wireless network. This architecture will be used in the dimensioning process to construct a bill of resources.

that they are part of a mobile network. Outdoor antennas are placed on the roof of the train, which maintain a wireless connection with base stations on the wayside or with a satellite in space. They are physically connected to the mobile gateway inside the train. The mobile gateway links the on-board local network to the outdoor antennas. This way, all passenger and operational data traffic can be transmitted via the mobile gateway and *via* the external antenna to the wayside.

As 3G and 4G data subscriptions are becoming more popular on consumer devices; direct communication from a device on-board with a network operator is also possible. One could therefore question the viability of installing a system with an integrated train-to-wayside communication system. However, direct communication from a device on-board with a wayside network operator suffers from signal attenuation which is one of the main reasons for the poor coverage of mobile networks inside a train. This is also the reason for frequent voice call drops on trains. Another benefit of the integrated train-to-wayside communication system is that it relieves all on-board devices from the burden of maintaining a connection at vehicular speed.

Three different kinds of wireless access technologies to provide train-to-wayside connectivity exist: satellite, cellular and dedicated wireless data networks [2]. A combination of these technologies is typically considered to be used for the train-to-wayside communication [2,4,6-8]. Table 1 gives an overview of these access technologies and is based on [2,9]. Using these values, one can obtain a rough idea of what the network will be able to provide in terms of bandwidth and latency.

Techno-economic model

Approach and methodology

Techno-economic modeling is used to evaluate technological solutions in different business environments. According to [25], four typical steps can be observed in techno-economic analysis for telecom deployment planning: scope definition, modeling costs and revenues,

Table 1 High-level overview of the characteristics of different wireless technologies

Parameter	Satellite network	Cellular networks	Wireless data networks
Bandwidth	High (2 to 50 Mbps)	Low to very high (0.17 to 14.4 Mbps) (4G: 0.1 to 1 Gbps)	High to very high (2 to 50 Mbps) (WiMAX 2: 0.1 to 1 Gbps)
Delay	(239.6 to 279.0 ms [10])	Low to very high (100 to 1,000 ms) (4G: <50 ms)	Very low (<50 ms)
Current coverage	International (but a clear line-of-sight is required)	National (good for standards up to 3G, for most recent standards not fully achieved)	Limited (new networks needed)
Maximum train speed	Very high (up to 500 km/h)	High (up to 250 km/h)	Low to high (120 to 250 km/h) (WiMAX 2: >250 km/h)
Technologies	DVB-S [11] DVB-S2 [14,15] DVB-RCS [18,19]	GPRS (2G) [12] EDGE (2.75G) [16] UMTS (3G) [20] HSPA (3.5G) [23] LTE (4G) [24] LTE-Advanced	Wi-Fi [13] Flash-OFDM [17] WiMAX [21,22]

evaluation of the business case and refinement of the results. This paper focuses on the first three steps.

In [26], the business model for broadband Internet on trains is investigated using a techno-economic model but only passenger Wi-Fi is considered as a service. In [8], a techno-economic inspection is done for three different user segments, that is passengers, freight companies and train operator's in house customers. This study recommends to implement all the services for different user groups on the same hardware equipment to reduce the investment cost. In [5], a cost modeling approach with multi-service analysis for broadband Internet on trains is presented but the allocation of unused capacity and the distribution of costs between different actors is not included in this approach. In our study, the cost modeling approach presented in [5] is extended to include the allocation of unused capacity. The multi-service cost model presented, allows to assess the costs of several services and to evaluate the investment decision for multiple actors.

In the first step of the techno-economic analysis cycle, the scope of the analysis is defined and input data is collected and processed. As shown in Figure 2, initial input data, which must be provided to the first part of the model are population of the train line to be studied, market share of the service operator and service penetration. These variables allow to determine the number of subscribers per service. In techno-economic analysis, the estimation of demand is a critical factor since the results are sensitive to these parameters. For our study, the parameters shown in Tables 2 and 3 are assumed. These variables allow us to determine the maximum population and the average population on the train. The data is obtained from a census conducted in 2009 [27] and from discussion with industry specialists. The number of boarding passengers is used to extrapolate the average number of passengers on the train line and the average trip time. The traffic demand per service, the number of subscribers per service, the bill of resources for each service and the QoS requirements for each service are used to calculate the service drivers. How to calculate these service drivers is described below. Other parameters to the dimensioning process are the rail parameters of Table 3 and the results from the GIS model described below. The output of the dimensioning process is a bill of resources.

The second step of the techno-economic analysis cycle is the modeling step. In this study, we focus on cost modeling. As such, the second part of the model is related to determining the cost of the dimensioned network. The bill of resources of the wayside resources, on-board resources and train-to-wayside resources is used as an input in this part. Other inputs are costs for the various network elements. These costs are listed in Table 4 and are obtained *via* desk research and refined *via* discussion with industry specialists with experience in the deployment of Internet services on trains. Costs are often expressed as Capital Expenditures (CapEx) and Operational Expenditures (OpEx); in this paper, no difference between the terms cost and

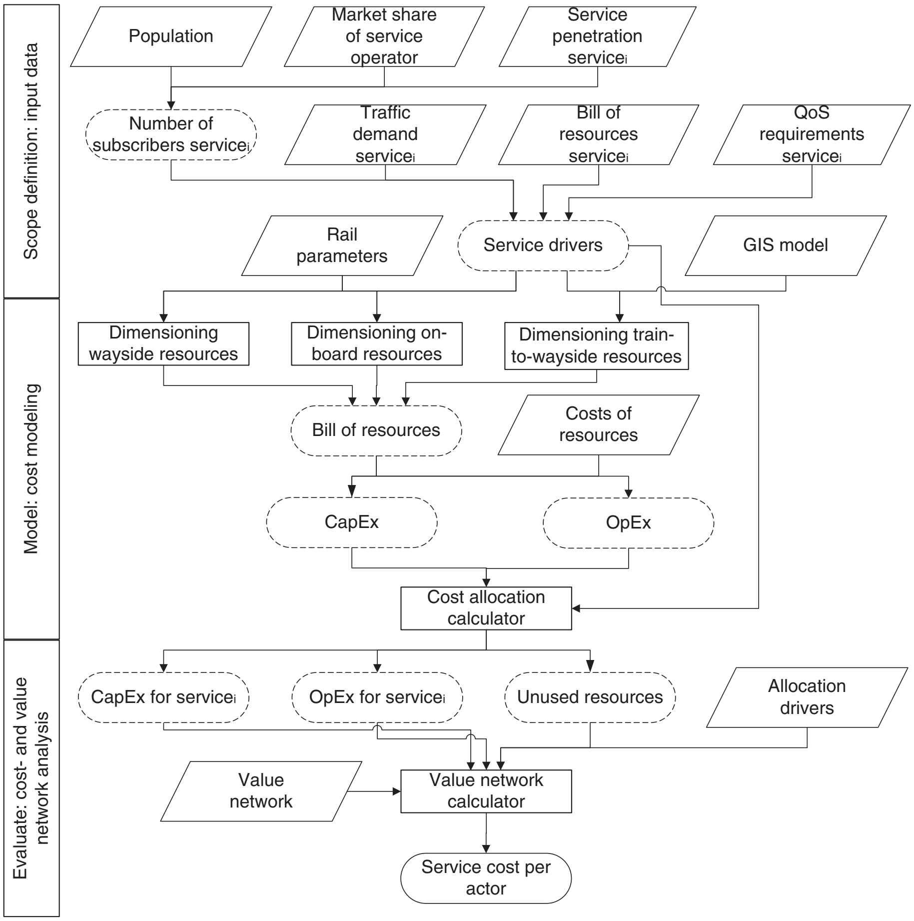

Figure 2 Flow diagram used in the techno-economic model. Assumption and input values are shown as a parallelogram, calculations are shown in rectangles, intermediate results are shown as an ellipse with a dashed line and final results are shown as an ellipse with a solid line.

expenditures is made. In [28], CapEx and OpEx are categorized. CapEx contribute to the fixed infrastructure of the company, and they are depreciated over time. CapEx include the purchase of land (e.g. site acquisition), network infrastructure (e.g. switches, routers), etc. OpEx do not contribute to the infrastructure; they represent the cost of keeping the company operational and include costs of technical and commercial operations, administration, etc. In our study, both CapEx and OpEx for a set of services are taken into account.

The third step in the techno-economic analysis cycle is the evaluation step. In this study, we focus on evaluating the cost of multiple services for multiple actors. The third part of the model is the allocation of costs to services and actors. The aim of our study is to perform a comparison for multiple actors between the deployment

Table 2 Parameters per service

Parameters	Free passenger Wi-Fi	Video-on-demand	Crew communication
Average adoption	20%/18%	3%	100%
Mbps downlink > Train	0.05 ppps	0.00 ppps	0.01 ptps
Mbps uplink > Wayside	0.05 ppps	0.00 ppps	0.01 ptps
Mbps downlink > Pass	0.05 ppps	1.00 ppps	0.01 ptps
Mbps uplink > Gateway	0.05 ppps	0.01 ppps	0.01 ptps
On-board storage (GB)	0	470	0

The adoption of passenger Wi-Fi is lower when the service is offered side-by-side with a video-on-demand service as these are competing services. ppps and ptps respectively stand for per passenger per second and per train per second, respectively.

Table 3 Parameters for the Belgian inter city line A between Oostende and Eupen

Parameter	Value
Number of trains	8
Number of cars per train	12
Number of trips per train (per day)	4
Maximum capacity of train (passengers)	878
Average number of passengers (per day)	10,822.12
Crew members on the train (FTE)	3
Total trip time (min)	181
Average trip time of a passenger (min)	34.66

cases with and without resource sharing. Therefore, we will first determine the resource consumption per service and the available capacity per resource. Next, we calculate the CapEx and OpEx per service and the unused resources. The previously obtained service drivers are inputs to the cost allocation calculator. How to calculate the unused resources and the CapEx and OpEx per service is described below. The value network configuration and allocation drivers are input to the final value network calculator. A value network generates economic value through complex dynamic exchanges between one or more enterprises, customers, suppliers, strategic partners and the community [29]. The exchanges between actors include transactions around goods, services and revenues but also knowledge value and intangible value or benefits. Our study considers only financial cost transactions around goods and services since the aim is to compare the costs for a service without or with resource sharing. The allocation drivers are used to distribute unused resources to a service. The end result of the model is the service cost per actor for a multi-actor, multi-service deployment.

Market assumptions

The target market of this study is the market for Internet services on trains, where the services are provided using an on-board Wi-Fi distribution network.

Services can be categorized in four distinct categories, pure passenger internet, passenger comfort services, safety- and security-related applications and cost-saving applications. These are discussed in more detail in [30].

The train operator considered in this paper is interested in offering three services on the Belgian inter city line between Oostende and Eupen (IC A): free on-board Wi-Fi, paid video-on-demand and crew communication. Each of these services will be provided to the users on their own connected device. A video-on-demand service with movies is especially interesting for long distance trajectories. To attract customers who spend less time on the train, the train operator will also offer shorter multimedia fragments such as TV-shows (typically between 20 and 40 min).

The service penetration for a free Wi-Fi service is assumed to be 20% when the service is offered as a stand-alone service and 18% when the free Wi-Fi service is offered in conjunction with a competing video-on-demand service. The service penetration for the video-on-demand service is assumed to be 3%. All crew members will switch at once to the new crew communication system.

Traffic demand is calculated considering the parameters in Table 2. The bandwidth for the Wi-Fi service and crew communication service is estimated at 0.05 and 0.01 Megabit per second (Mbps) per passenger, respectively. This amount of bandwidth has to be provided by a connection both on-board the train as well as between the train and the wayside during the entire travel time. The video-on-demand service stores data on-board the train to limit the traffic between the train and the wayside. A 470 GigaByte (GB) video-on-demand server is used for this purpose. The video-on-demand service does not require a continuous connection to the wayside. New content can be uploaded at specific locations where cheap bandwidth is available. Examples are stations and depots equipped with Wi-Fi. To distribute the videos from the on-board server to the passengers, the on-board Wi-Fi network is used and video is streamed at a rate of 1 Mbps. The yearly volume of data transmitted is calculated according to Equation 1, where $\overline{u_i}$ are the average number of users per year of service$_i$, $\overline{t_i}$ is the average time a user uses service$_i$ in seconds and DL_i and UL_i are the downlink and uplink bandwidth demands of service$_i$ per second. The maximum throughput is calculated according to Equation 2, where $u_{\max,i}$ is the maximum number of users of service$_i$.

In this article, the uplink and downlink bandwidth demands of a service are aggregated as for the selected technologies (i.e. 3G and Wi-Fi) this approach is adequate. Nevertheless, services such as a video-on-demand service, software download and video file download have bandwidth requirements dominated by the downlink bandwidth demand while other services such as CCTV may have bandwidth requirements dominated by the uplink bandwidth demand. By taking the asymmetric bandwidth demand by the service and asymmetric bandwidth supply by the access network into account, resource usage may be further optimized.

$$\text{Yearly data volume} = \sum_{i=1}^{n} \overline{u_i} \times \overline{t_i} \times (\mathrm{DL}_i + \mathrm{UL}_i) \qquad (1)$$

$$\text{Max throughput} = \sum_{i=1}^{n} u_{max,i} \times (\mathrm{DL}_i + \mathrm{UL}_i) \qquad (2)$$

Table 4 Network element components and per-unit cost assumptions used in the techno-economic model

Network element/asset	Per unit purchase price (euro)	Per unit installation cost (euro)	Per unit operating expense (euro)	Asset lifetime (year)	Resources per unit	Resources required
On-board						
WAPs	750.00	100.00	75.00	10.00	2/car	192
Wiring	2.00	2.00	0.20	10.00	200/car	19,200
Gateway server	2,500.00	1,600.00	250.00	10.00	2/train	16
Switch	750.00	100.00	75.00	10.00	1/car	96
Video-on-demand server	4,000.00	100.00	400.00	10.00	2/train	16
Crew mobile device	300.00	100.00	30.00	11.00	3/train	24
Antenna (Cellular, Wi-Fi)	750.00	100.00	75.00	10.00	8/train	64
Splitter	300.00	100.00	30.00	10.00	8/train	64
Radios	300.00	100.00	30.00	10.00	16/train	128
Train-to-wayside						
Data over Cellular (GB)	0.00	0.00	7.50		17,556	17,556
Data over Wi-Fi (GB)	0.00	0.00	0.25		924	924
Wayside						
Content creation server	0.00	0.00	3,600.00		2 cloud servers	2 cloud servers
Management server	0.00	0.00	3,600.00		2 cloud servers	2 cloud servers
Gateway server	0.00	0.00	3,600.00		2 cloud servers	2 cloud servers
Network support	0.00	0.00	52,000.00		2 FTE	2 FTE

Rail parameters

To illustrate the proposed approach, we consider a train operating company that is planning to offer Internet services on-board its fleet. The target market is the IC A line between Oostende and Eupen. Each train will be refurbished, and during the refurbishment, the cabling can be placed in the floors and roofs for an on-board network. A single trip from Oostende to Eupen takes 181 min; trains leave the station every hour and eight different trains are used to operate this route. Each train does 4 trips per day; is composed of a single locomotive, 11 passenger cars, and a single cab car and can carry 878 passengers. The average number of passengers per day is 10,822.12 and the average trip time of a passenger is 34.66 min. Per train, three crew members are on-board. These parameters are summarized in Table 3.

Service drivers

The technical architecture from the 'Technical solutions to providing Internet services on trains' section gives a high-level view of the (sub)systems required to provide Internet services on trains. To investigate the impact by the different services on resource consumption, we analyze the technical architecture in detail to come to a low-level list of service drivers.

Three types of service drivers are used in this paper: traffic-related, bill of resource-related and QoS-related service drivers. The service drivers are input to the dimensioning process.

The traffic-related service drivers refer to the maximum throughput and the yearly data volume consumed by a service. These are calculated according to Equations 1 and 2. The yearly consumed data volume is used to dimension the train-to-wayside communication over cellular and over Wi-Fi. The maximum on-board throughput per car is the minimum capacity of the wireless access points (WAPs) the wiring and switches on-board the train have to be able to transmit. The maximum train-to-wayside throughput per train is the minimum capacity the on-board gateway servers, antennas, splitters and radios should be able to transmit.

The bill of resources-related service drivers refer to the set of resources that are required per service. The free Wi-Fi service and the crew communication service share usage of the same on-board and wayside resources but the crew communication service uses dedicated crew mobile devices. The video-on-demand service shares usage of the on-board distribution network and the wayside resources with the other services and uses a dedicated video-on-demand server on-board the train and a dedicated content creation server at the wayside. The video-on-demand server and the content creation server need to be able to store 470 GB. We assume that all content is updated once per year. As such, 470 GB has to be transferred per train over Wi-Fi for the video-on-demand service. The connection to the wayside uses an on roof antenna system consisting of the antenna itself, a signal splitter and radios that receive and transmit the signal. Coaxial cables interconnect the roof antenna system with the on-board equipment. The on-board network equipment consists of an on-board gateway server which will direct the traffic from the offered services to the right destination. A Wi-Fi distribution system is deployed to bring the service to the customer. The Wi-Fi distribution system consists of WAPs attached to the ceiling of the carriages that are connected *via* Category 5e UTP cables to the on-board servers and access routers. Switches are used to interconnect all network elements efficiently. The passenger services are offered *via* their own devices (e.g. laptop, smartphone or tablet), the crew communication service is offered on mobile devices that are included in the service offering. On-board the train, a video-on-demand server is deployed. For the train-to-wayside connection, multiple technologies and/or network operators can be used. For the case considered, the existing cellular infrastructure and Wi-Fi access points of a single network operator are used to transmit and receive data signals. For this case, this combination of technologies is adequate, but for other areas, the offered bandwidth may not be sufficient and a satellite connection or the deployment of a dedicated Wi-Fi/WiMAX network can be considered. At the wayside, a manned network operations center has to be set up to provide support for network maintenance, upgrades and failures. Several servers are required to provide the services. A wayside gateway server which is complementary to the on-board gateway server directs the traffic to the right destination. A server is required for the management of the services and a content creation server is used to update the video content.

The QoS-related service drivers refer to the quality requirements that are expected per service. The following quality requirements were identified: the services should be available in all train cars, the train-to-wayside connection should cover at least 95% of the trajectory, network support should be available during the whole time the train fleet is active and the wayside management server, gateway server and content creation server should be available 99.99% of the time.

Geographic information system model

A geographic information system (GIS) data model is used to estimate network coverage for a given bandwidth demand along the train track. For a given train line, the GIS model takes into account the downlink and uplink bandwidth requirements, the number of active users and the movement of the train.

The data set includes two layers. The first layer includes the position of the train tracks which is based on data from the OpenStreetMap project [31]. The second layer includes the position of the cellular antennas which is based on data from the Belgian regulator [32] and the cell size (see below). When the first layer is overlaid with the second layer, the amount of non-covered track is apparent.

To estimate the cell size covered by a base station, a link budget has to be determined. The link budget takes all the gains and the losses that occur during the propagation through the medium from the transmitter to the receiver into account. The link budget is needed to calculate the maximum allowable path loss PL_{max} (in dB) to which a transmitted signal can be subjected while still being detectable by a receiver. Once the maximum allowable path loss PL_{max} is known, the maximum cell size (in meters) covered by a base station can be determined *via* a path loss model (PLM). A PLM takes into account PL_{max}, the shadowing margin, the frequency, the height of the base station and the height of the mobile base station. Further, we apply a Doppler margin of 3 dB [9] in order to take speeds up to 150 km/h into account. Here, the Erceg B path loss model [33] is assumed to determine PL_{max} and the cell size.

The area to be covered with a train-to-wayside connection is the rail corridor where the trains pass through. The GIS model described above is used to estimate the coverage rate of the rail corridor based on the legacy network of the mobile network operator. We use the GIS model to calculate if coverage by the legacy network is sufficient (minimum 95%). If not, extra radio base stations are required. A genetic algorithm is used to calculate the amount of additional radio base stations that are needed to reach the minimum coverage rate. We assume that on-board signal repeaters are installed on the train to overcome attenuation losses. To provide the trains with a connection with the required bandwidth, the 3G network of Proximus, a Belgian network operator was considered. Since the cellular network is a shared resource, a number of users will be active within the cell that are not on the train (we assume six extra users). On certain special occasions, the number of active users could be even higher. For example, when another train crosses or when an event is organized near a train line. For the case considered, bandwidth requirements are set at peak traffic demand of two crossing trains at peak capacity increased with six additional users who are not on the train. The output of the GIS model indicates, for the assumed parameters, that the available cellular network of Proximus can provide adequate bandwidth when on-board signal repeaters are deployed. As such, no extra radio base stations need to be deployed. Note that without on-board signal repeaters 109, 282 and 594 additional radio base stations have to be deployed to provide a data connection of respectively 1, 3.6 and 7.2 Mbps to the train.

Network dimensioning

Network dimensioning aims at calculating the optimal number of network elements, which fulfill the requirements summarized by the service drivers in the service area at minimal total costs [34]. The network architecture considered in this study is described above.

The costs associated with the network depend on the services that will be offered, the number of subscribers and the total traffic demand. The required network elements are divided in four areas as already indicated in Figure 1: on-board, train-to-wayside, integrator and wayside infrastructure.

The dimensioning process is based on [5] supplemented with desk research and discussion with partners internal to the RAILS consortium. We illustrate the dimensioning process for WAPs, the antenna system and network support. The typical number of WAPs per carriage is two but this can vary depending on the layout and length of the carriage. The number of WAPs is also dependent on the expected service demand. The threshold for a decent connection will vary according to the bandwidth demand per user. When the number of connecting passengers is above this threshold, the service operator should consider adding an extra WAP. Based on expert opinion, we estimate that an industrial grade WAP can support 60 concurrent connections of 1 MB. For the case considered, 2 WAPs per rail car will be sufficient. A train will typically install several antennas which each make an individual connection to the wayside. Per train, eight antennas will be installed. For each antenna, a signal splitter is required, a transmitter radio and a receiver radio. Network support is provided by a manned network operations center. The QoS service drivers require that network support should be available during the whole time the train fleet is active. As such, a minimum of two full-time employees (FTEs) are needed. These can support a total of five services.

A summary of the required resources is given in the 'Resources required' column of Table 4 and of the capacity of each resource in terms of used capacity service drivers in the 'Capacity' column of Table 5.

Investment and operating cost assessments

The result of the 'Network dimensioning' section is a bill of resources. In general, obtaining an exact prediction of the deployment cost of a network is difficult as a consequence of the many different factors that affect the result. To deal with this complexity, the per-unit investment (purchase price and installation cost) and operating costs assumed in this article are based on the costs provided by partners in the RAILS consortium which consist of a train operating company, network operator, equipment manufacturer, an integrator and a service provider.

In order to calculate total network-related and service-related costs, annualized investment- and operating

Table 5 Overview of the used capacity per service and the available capacity per resource for both cases

Network element/asset **Actor from**	**Actor to**	**Capacity**	**Cost type**	**Used capacity passenger Wi-Fi** **(case 1/2) TOC**	**Used capacity video-on-demand** **(case 1/2) SP**	**Used capacity crew communication** **(case 1/2) SP**	**Unused capacity**
On-board							
WAPs (connections)	INT	75.00	Shared	26.34/23.71	0.00/3.95	0.00/3.00	48.66/44.34
Wiring (Mbps)	INT	100.00	Shared	1.46/1.32	0.00/2.22	0.00/0.02	98.54/96.45
Gateway server (Mbps)	INT	170.45	common	31.61/28.45	0.00/0.00	0.00/0.02	138.84/141.98
Switch (Mbps)	INT	80.00	Shared	1.46/1.32	0.00/2.22	0.00/0.02	78.54/76.45
Video-on-demand server (unit)	INT	1.00	Direct	0.00/0.00	0.00/1.00	0.00/0.00	0.00/0.00
Crew mobile device (units)	INT	3.00	Direct	0.00/0.00	0.00/0.00	0.00/3.00	0.00/0.00
Antenna (Mbps)	INT	170.45	Common	31.61/28.45	0.00/0.00	0.00/0.02	138.84/141.98
Splitter (Mbps)	INT	170.45	Common	31.61/28.45	0.00/0.00	0.00/0.02	138.84/141.98
Radios (Mbps)	INT	170.45	common	31.61/28.45	0.00/0.00	0.00/0.02	138.84/141.98
Wayside							
Data over cellular (GB data)	NOP		Direct	19,507/17,556	0.00/0.00	0.00/301.26	
Data over Wi-Fi (GB data)	NOP		Direct	c1,027.69/924.02	0.00/3,760.00	0.00/15.86	
Integrator/train-to-wayside							
Content creation server (GB)	INT	470.00	Direct	0.00/0.00	0.00/470.00	0.00/0.00	0.00/0.00
Management server (services)	INT	5.00	Shared	1.00/0.00	0.00/1.00	0.00/1.00	4.00/2.00
Gateway server (services)	INT	5.00	Shared	1.00/0.00	0.00/1.00	0.00/1.00	4.00/2.00
Network support (services)	INT	5.00	Shared	1.00/0.00	0.00/1.00	0.00/1.00	4.00/2.00

The table includes the amount of unused capacity and the cost type of each resource. The financial cost flows between the actor who offers the service (actor from) to the actor that offers the resources (actor to) are also indicated.

expenses are obtained from the per-unit cost assumptions and the network dimensioning solutions. Respectively, Equations 3 and 4 are used to calculate the CapEx and OpEx of a resource with R_i for resource$_i$. An overview of the resources required is given in Table 4.

$$\begin{aligned}\text{CapEx } R_i =& \\ &\text{Resources required } R_i \\ &\times (\text{Purchase cost } R_i \\ &+ \text{Installation cost } R_i)\end{aligned} \tag{3}$$

$$\begin{aligned}\text{OpEx } R_i =& \\ &\text{Resources required } R_i \\ &\times \text{Operational cost } R_i\end{aligned} \tag{4}$$

The different assets are classified in three groups (on-board, train-to-wayside and integrator/wayside) as presented in Table 4.

Service cost assessment and unused resources

Once the investment and operating cost assessment has been concluded, the service cost can be obtained. As indicated in Figure 2, a selection of the service drivers is used in the cost allocation calculator that is described in this section. For future reference, these service drivers are identified as 'used capacity' service drivers. The peak number of active connections is used for the WAPs. The maximum on-board throughput per car is used for the wiring and the switches. The maximum train-to-wayside throughput per train is used for the gateway servers, antennas, splitters and radios. The yearly consumed data volume is used for the train-to-wayside communication. The used capacity service driver for the other resources is a dummy variable that indicates if the service uses the resource or not.

Costs can be categorized in three categories according to the way they consume resources. Direct costs are related to resources that are directly attributable to one service such as a dedicated video-on-demand server, a dedicated content creation server or usage of the train-to-wayside communication. Common costs are costs related to resources that are shared by several services but not all. An example is the antenna system installed on-board the train. Shared costs (sometimes also called joint costs) are shared by all services. Examples are the on-board Wi-Fi distribution system and the wayside management and gateway server and network support. An overview of the classification of costs is given in the 'Cost type' column of Table 5.

Direct costs of a resource are obtained according to Equations 5 and 6. S_j is the respective service$_j$, R_{ij} is the considered resource$_i$ of service$_j$. We refer to Table 5 for an overview of the used capacity service drivers. The CapEx and OpEx of a resource has been determined before according to Equations 3 and 4.

$$\text{CapEx } S_j = \sum_{i=1}^{n} \frac{\text{Used capacity } R_{ij} \times \text{ CapEx } R_i}{\text{Capacity } R_i} \tag{5}$$

$$\text{OpEx } S_j = \sum_{i=1}^{n} \frac{\text{Used capacity } R_{ij} \times \text{ OpEx } R_i}{\text{Capacity } R_i} \tag{6}$$

To distribute common and shared costs to a service, a cost allocation procedure is used. Among the most used allocation procedures are Stand-Alone Costing (SAC) and Fully Allocated Costing (FAC) [35].

In SAC, the service cost is considered as if it was the only service the company produced. In this way, it includes all direct costs and it sums up the joint and common costs entirely. The stand alone cost is the highest cost level the service can reach, and is used as a reference in this sense.

In FAC, all costs that are incurred in the production of services are allocated across those services. Fully allocated costs will include a share of common costs and joint costs that span activities, i.e. all costs directly and indirectly attributable to the service, plus shares of those costs with no direct causal relationships. FAC requires criteria to attribute common and joint costs. In this study, the used capacity service drivers are used to allocate joint and common costs to a service according to Equations 5 and 6.

In the typical situation of a network service, there exists some unused capacity due to two factors: on the one hand, a certain over-dimensioning due to the expected traffic growth and, on the other, the technical modularity of equipment.

To allocate these resources, the unused capacity criteria are needed. These criteria are typically driver based, and we use allocation drivers to allocate unused resources to a service according to Equations 7 and 8. Among the most used allocation drivers are those that distribute costs based on the amount of services produced with respect to the overall company service production, those that distribute costs proportionally to the amount of gross revenues with respect to the overall company gross revenue and those that distribute costs to services proportionally to the amount of net revenues attributable to it with respect to the overall company net revenues [35]. A drawback of these criteria is that typically a single benchmark is used to distribute the total unused capacity between services. In this study, the used capacity service drivers are used as allocation driver. A benefit of this approach is that the unused capacity of every resource is distributed according to a specific criterion. This is however only one of several possible options that can be used. In general, the allocation drivers should be tailored to the specific case.

$$\text{Unused CapEx } S_j = \sum_{i=1}^{n} \frac{\text{Allocation driver } R_{ij} \times \text{Unused CapEx } R_i}{\sum_{j=1}^{m} \text{Allocation driver } R_{ij}} \tag{7}$$

$$\text{Unused OpEx } S_j = \sum_{i=1}^{n} \frac{\text{Allocation driver } R_{ij} \times \text{Unused OpEx } R_i}{\sum_{j=1}^{m} \text{Allocation driver } R_{ij}} \tag{8}$$

Value network

This section describes the key stakeholders in the rail industry and introduces the value network configuration used in this study. In [30], a value network analysis is carried out about Internet deployments on-board the train.

The first block are the wayside roles. The railway infrastructure owner operates the physical rail infrastructure and charges operating companies to use it. Train operating companies provide retail services to passengers and freight customers. The train owner owns train vehicles. The train operating company may not be the owner of the train vehicles; in such cases, the train owner leases train vehicles to train operating companies. The rail supply industry comprises a wide range of contractors such as train maintainer companies who maintain the train, integrators who provide component systems and implementation support and service providers.

The second block are the roles that provide the physical and logical network connection. Network operators provide the physical network connection. Integrators provide the logical network connection, they are responsible for the development, installation and maintenance of the systems (e.g. authentication, addressing and security).

The third block are the end users on-board the train: the train (machine-to-machine communication), train passengers and the train crew.

The value network configurations for two scenarios used in the techno-economic analysis are shown in Figure 3. For a summary of the value exchanges (cost transactions), we refer to Table 5. The ‘Actor from’ row in Table 5 indicates which actor offers a service. The ‘Actor to’ column in Table 5 indicates which actor provides a resource to the service provider. The value exchange can be reconstructed by connecting both columns. For example, the service provider bears the cost of the train-to-wayside communication for the video-on-demand service and the crew communication service. The fee for the physical connection is, as indicated in Figure 3, transferred *via* the train operating company to the network operator.

Service cost per actor

By combining the obtained CapEx and OpEx per service on the one hand and the value network configurations on the other, we obtain the cost per service and per actor. Equation 9 is used to calculate the financial cost flows for service$_i$ from actor$_k$ to actor $_l$ (FCF$_{ikl}$) with S_{ikl} the share of resource$_i$ used by actor$_k$ for the resources provided by actor$_l$.

$$\begin{aligned}\text{FCF}_{ikl} = {} & \\ & S_{ikl} \times (\text{CapEx}_i \\ & + \text{OpEx}_i + \text{unused CapEx}_i \\ & + \text{unused OpEx}_i)\end{aligned} \tag{9}$$

The obtained costs per service and per actor let us draw conclusions of the economic benefit of resource sharing by comparing costs of a deployment with and without resource sharing, as presented below.

Main results and discussion

The technical model to provide Internet services on trains and the techno-economic model described in the previous sections have been combined in order to obtain the service cost per actor for the deployment on the Belgian IC A train line between Oostende and Eupen. Three services are analyzed for the deployments. A free passenger Wi-Fi service that passengers can use to browse the Internet and check their email while traveling. A paid video-on-demand service that offers movies and television shows as entertainment. A crew communication system is used by the crew members for train-to-wayside communication.

A comparison is performed between the economic cost provided by the stand-alone deployment of the passenger Wi-Fi service and the joint deployment with the other services. In addition, the cost per service and per actor is discussed for both cases. In the base case, a service operator deploys a free Wi-Fi service for passengers on the train. In the shared services case, different service operators deploy free Wi-Fi, video-on-demand and crew communication.

Single service case

The assumptions for the single service case of the study draw a scenario where the train operating company deploys a new on-board network to offer free Wi-Fi to passengers. The existing network of the network operator is used for the train-to-wayside connection. Based on the GIS model described above, we can conclude that adequate bandwidth is provided by the network operator’s

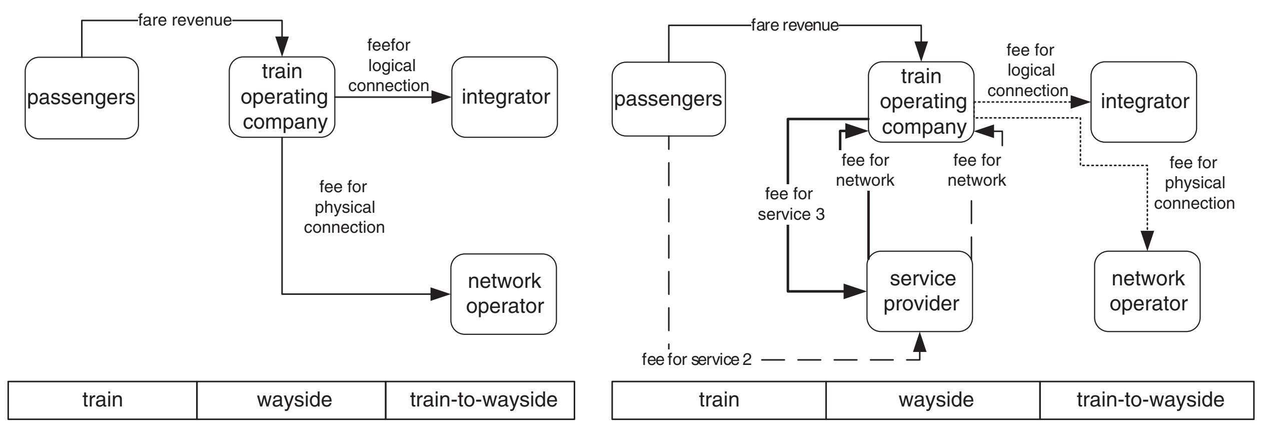

Figure 3 Value network configurations used in the techno-economic model. Service 1: free passenger Wi-Fi; service 2: video-on-demand; service 3: crew communication. In the first scenario (left side), a train operating company offers free passenger Wi-Fi. To cover the cost, a charge is included in the ticket fee. In the second scenario (right side), the free passenger Wi-Fi service is complemented with a video-on-demand service and a crew communication system. Both are provided by a third party (service provider). All services use the communication network which is operated by the integrator (logical connection) and the network operator (physical connection). The train operating company pays a contractual fee for the network connection and charges the service provider a fee for usage of the network.

cellular network. The network operator also operates a Wi-Fi network in all rail stations that is preferred above the cellular network when the trains are in reach. It is assumed that the Wi-Fi network can be used for 10% of the total trip time.

Table 6 shows the annualized deployment cost and the used and unused capacity. Results show that OpEx has the highest share. The main costs are the fee the train operating company pays to the network operator for train-to-wayside communication and the fee for network support by an integrator. The train-to-wayside resources, and wayside servers are 100% used. These resources can be purchased in the quantity required. The wayside servers for example run on cloud servers with a pay for usage plan.

Table 6 Annualized deployment cost for single service case and an overview of used and unused capacity per resource

	Capex (euro)	OpEx (euro)	Used capacity (euro)	Unused capacity (euro)
On-board				
WAPs	16,320.00	14,400.00	10,788.86	19,931.14
Wiring	7,680.00	3,840.00	168.58	11,351.42
Gateway server	6,560.00	4,000.00	1,958.23	8,601.77
Switch	8,160.00	7,200.00	280.96	15,079.04
Video-on-demand server	0.00	0.00	0.00	0.00
Crew mobile device	0.00	0.00	0.00	0.00
Antenna (Cellular, Wi-Fi, GPS)	5,440.00	4,800.00	1,898.89	8,341.11
Splitter	2,560.00	1,920.00	830.76	3,649.24
Radios	5,120.00	3,840.00	1,661.53	7,298.47
Train-to-wayside				
Data over Cellular	0.00	146,302.70	146,302.70	0.00
Data over Wi-Fi	0.00	256.67	256.67	0.00
Integrator/train-to-wayside				
Content creation server	0.00	0.00	0.00	0.00
Management server	0.00	7,200.00	1,440.00	5760.00
Gateway server	0.00	7,200.00	1,440.00	5760.00
Network support	0.00	104,000.00	20,800.00	83,200.00
Total cost	51,840.00	304,959.37	187.827.18	168.972.18

Table 7 Annualized deployment cost for the multi-service case and an overview of the used and unused capacity per resource and per service

	CapEx (euro)	OpEx (euro)	Used capacity passenger Wi-Fi (euro)	Used capacity video-on-demand (euro)	Used capacity crew communication (euro)	Unused capacity (euro)
On-board						
WAPs	16,320.00	14,400.00	9,709.98	1,618.33	1,228.80	18,162.89
Wiring	7,680.00	3,840.00	151.72	255.39	2.30	11,110.58
Gateway server	6,560.00	4,000.00	1,762.41	0.00	1.24	8,796.35
Switch	8,160.00	7,200.00	252.86	425.65	3.84	14,677.64
Video-on-demand server	6,560.00	6,400.00	0.00	12,960.00	0.00	0.00
Crew mobile device	960.00	720.00	0.00	0.00	1,680.00	0.00
Antenna (Cellular, Wi-Fi, GPS)	5,440.00	4,800.00	1,709.00	0.00	1.20	8,529.80
Splitter	2,560.00	1,920.00	747.69	0.00	0.53	3,731.79
Radios	5,120.00	3,840.00	1,495.38	0.00	1.05	7,463.57
Train-to-wayside						
Data over Cellular	0.00	133,931.85	131,672.43	0.00	2,259.42	0.00
Data over Wi-Fi	0.00	1,174.97	231.00	940.00	3.96	0.00
Integrator/train-to-wayside						
Content creation server	0.00	7,200.00	0.00	7,200.00	0.00	0.00
Management server	0.00	7,200.00	1,440.00	1,440.00	1,440.00	2880.00
Gateway server	0.00	7,200.00	1,440.00	1,440.00	1,440.00	2880.00
Network support	0.00	104,000.00	20,800.00	20,800.00	20,800.00	41,600.00
Total	59,360.00	307,826.82	171,412.47	47,079.38	28,862.35	119,832.63

In contrast, a fraction of network support and on-board resources are used. The reason is found in the technical modularity of equipment and the need for two full-time employees for network support that are available at any time.

Multi-service case

The assumptions for the multi-service case of the study draw a scenario where free Wi-Fi, paid video-on-demand and crew communication are offered. When passenger Wi-Fi and video-on-demand are available, users of the free Wi-Fi service may shift to the video-on-demand service. We therefore assume a lower adoption for free passenger Wi-Fi (i.e. 18%). All other assumptions remain the same.

Table 7 shows the annualized deployment cost, the used capacity per service and the unused capacity. Similar to the single service case, OpEx has the highest share in the total cost. Both the video-on-demand and crew communication share usage of many network elements with the Wi-Fi service. The video-on-demand service requires an extra on-board server and a wayside content creation server to store and upload content. The crew communication service uses mobile devices for the crew which are not required for any other service. Both services are not traffic intensive. The video-on-demand service stores the content on-board the train to limit the transfers of data between the train and wayside and uploads new content overnight when Wi-Fi is available.

Case comparison

Figure 4 summarizes the results of the first step. In the first step, the proposed method is used to evaluate if an opportunity exists to increase the utilization of resources. It gives insights in the total cost and the cost of used and unused resources. Several scenarios can easily be compared. The total cost in the multi-service case is higher in comparison to the single service. This is logic as more resources are required. On the one hand, new resources are needed such as crew mobile devices and a content creation server. On the other hand, a higher quantity of the resources that are already used at full capacity in the single service case are needed, examples are train-to-wayside communication and usage of the wayside cloud servers. The fraction of used resources is increasing while the amount of unused resources is decreasing in a multi-service case. Results show that several of the resources with spare capacity in the single service case can be shared with the additional services. An example is the antenna system on the train which can be used by several services at the same time to transmit data from the train to the wayside. Another example are the employees that run network support. Their job does not change significantly when extra services are added while their salary can now be shared among several services.

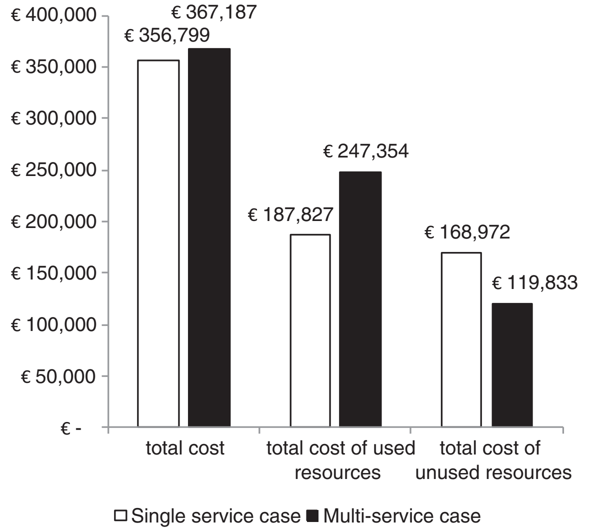

Figure 4 Cost comparison between single service and multi-service case. Annualized total cost is increased with 2.91% in the multi-service case while the utilization rate of the resources is increased with 14.72%.

Figure 5 illustrates the obtained results of the second step. In the second step, the model is used to determine the cost per service and to evaluate if an opportunity exists to reduce the total cost of a service. The method gives insights in the cost per service and the main contributors to the cost of a service. Resources are allocated to services based on the used capacity service drivers (Table 5). The unused resources are allocated to a service based on the selected allocation drivers. In this study, the used capacity service drivers are also adopted as allocation drivers. In the single service case, all costs are allocated to a single service. Therefore, the fully allocated cost for passenger Wi-Fi is equal to the stand-alone cost. In contrast with the single service case, the cost of unused resources can be split among several services in the multi-service case. A high amount of unused resources increases the benefit of resource sharing which in turn reduces the total cost of each service. Results show that the total cost for the Wi-Fi service is reduced significantly for the resources that have the lowest utilization rates. In terms of categories, the higher savings are related to the on-board resources and network support. These resources have a modular nature and capacity cannot be increased or reduced flexibly which leads to unused capacity and higher costs in contrast to resources that can be purchased in the quantity needed.

Figure 6 summarizes the results of the third step. In the third step, the proposed method is used to determine the financial cost flows per service between actors. The financial cost flows between actors for both cases are obtained. The financial cost streams to offer a service are

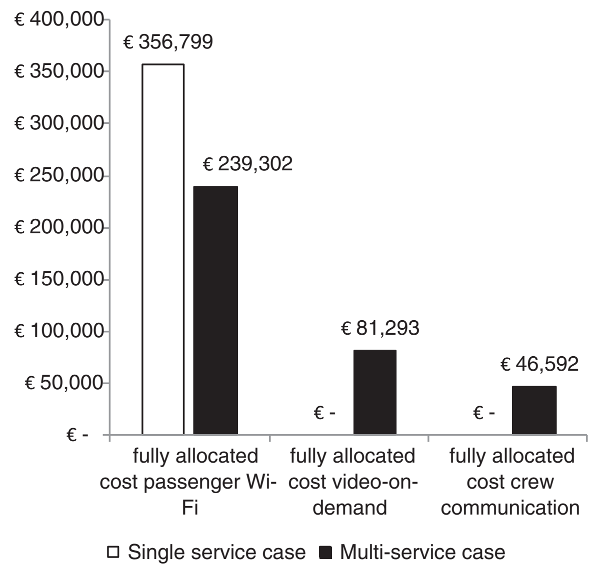

Figure 5 Cost comparison per service between single service and multi-service case. In this case, the fully allocated cost for the free passenger Wi-Fi service can be reduced by 32.93% in a multi-service case. The reason for the reduction is more efficient usage of resources *via* cross service resource sharing.

summarized in Figure 3. In Table 5, the streams are specified per resource, the 'Actor from' pays to the 'Actor to' for the provided resources. In the single service case, the train operating company pays most for the services provided by the integrator while this amount is spread among the service provider and the train operating company in the multi-service scenario. The reason for this reduction is that the resources provided by the integrator can be shared by several services. The cost flow between the train operating company and the network operator is reduced in the multi-service case in comparison to the single service case. This is due to lower usage of train-to-wayside communication by the Wi-Fi service in the multi-service case as some users will shift from using the free Wi-Fi service to the paid video-on-demand service while both the crew communication service and the video-on-demand service require only limited train-to-wayside communication. As the resources provided by the network operator are provided as required, resource sharing has no effect on the related cost flows.

The proposed model can easily be extended to include the revenues per service to provide ex-ante insights in the profitability of a service per involved actor. In addition, the model can be used as basis for pricing of resources and services when cost-based pricing is applied based upon resource and service usage.

Conclusions

Current techno-economic evaluation models are hard to apply to cost allocation in a multi-service deployment with multiple actors and resource sharing. We therefore propose a new evaluation model and apply it to a deployment of Internet services on trains.

The proposed techno-economic model has been applied to the deployment of Internet services on trains in order to assess the economic gains provided by a multi-service deployment with resource sharing in comparison to a single service deployment. For this purpose, the challenges to providing a continuous mobile signal on the train have been described and the architecture required to provide Internet access on-board the train has been analyzed, which in turn allows the dimensioning of the on-board, train-to-wayside and wayside resources. For each resource, we investigated the impact by different services on resource consumption; as such, we could allocate the used and unused resources to the appropriate services. In a final step, based on value network analysis, we distributed the costs of a service between actors.

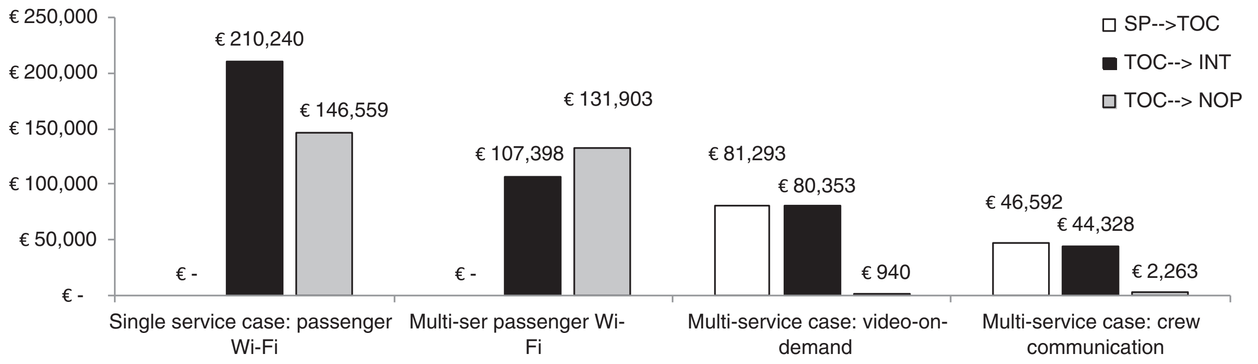

Figure 6 Comparison of financial cost flows between single service and multi-service cases. For this study, in the multi-service case, the train operating company reduces the net amount he has to pay to the integrator in comparison to that in the single service case. For video-on-demand and crew communication, the train operating company acts as an intermediary between the service provider and the integrator/network operator.

The scenario analyzed represents three services that are deployed on the Belgian IC A train line but similar analysis can be done for other services and other train lines. The study analyzed deployments of a single service by multiple actors in comparison to multiple services by multiple actors with resource sharing. Under this framework, economic gains in terms of cost savings provided by the shared usage of resources by multiple services have been estimated. In addition, the cost per service per actor is determined and analyzed.

Our analysis includes the deployment cost (CapEx and OpEx) of the on-board resources, the train-to-wayside connection and the wayside resources. For this case, the GIS-based tool that is used to evaluate the train-to-wayside connection shows that enough bandwidth is available on the IC A train line when on-board equipment is installed to overcome signal attenuation by the train carriage. As such, the train-to-wayside communication can be provided by a network operator who charges a fee based on the actual usage. The results show that resource sharing by multiple services will not reduce the cost of these flexible resources for a service. In contrast, for the considered case, the on-board resources and wayside network support can be shared among multiple services as unused capacity exists. A high amount of unused resources increases the benefit of resource sharing which in turn reduces the total cost of each service. Our results show that the cost of providing a Wi-Fi service on-board the train can be reduced significantly when other services with overlapping resource demand are offered. The obtained results of this analysis are case dependent but the general results of this study will remain applicable.

By applying the proposed techno-economic model to the deployment of Internet services on trains, we show its main benefits. The proposed model produces insights in the total cost, the cost of used and unused resources and the contributors to the cost per service, per actor. In addition, the model can be used as basis for pricing of resources and services when cost-based pricing is applied based upon resource and service usage. Finally, when the revenues of a service can be estimated, the profitability per actor, per service can be evaluated. As a consequence, the proposed model should be considered to support and stimulate multi-actor investment decisions for Internet-based multi-service offerings on-board trains with resource sharing.

Future work will focus on extending this framework to include deployment of other on-board access technologies such as femtocell access points and the extension towards revenue modeling.

Abbreviations

ABC: activity-based costing; CapEx: capital expenditures; FAC: fully allocated costing; FTE: full-time employee; GB: gigaByte; GIS: geographic information system; Mbps: megabit per second; OpEx: operational expenditures; SAC: stand-alone costing; WAP: Wi-Fi access point; Wi-Fi: wireless fidelity.

Competing interests

The authors declare that they have no competing interests.

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