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Design of a Web-Based Decision Support System for Service Portfolios in Heterogeneous Radio Access Network Environments

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Abstract Newly emerging radio access technologies have produced a novel heterogeneous network environment. Wireless service operators should build the best service portfolio strategy for each user by focusing on the co-existence of multiple access networks and complex service combinations, while maximizing the overall network utilization. Web-based Decision Support System (web-based DSS) is one of the best ways of making service portfolios available to every user in a multiple access network environment. Service designers, customer relationship managers, and network engineers can build the best match relationship between services and networks to enhance user utilization. In addition, the easily accessible web-based DSS in an optimal heterogeneous network operation framework provides opportunities for designing new services. The network load and financial effect of newly designed services could also be analyzed and reshaped easily by testing the DSS functionality. Various mathematical tools have been developed for DSS to integrate different network domains. To demonstrate its applicability to the integration of network domains, we tested various service scenarios in a heterogeneous network environment and evaluated the versatile functions of web-based DSS.

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1 Introduction

Wireless communication networks have experienced drastic growth in recent years, which has led to fundamental changes in the communications paradigm. User-oriented technological advances have been developed to provide various services to users with different traffic characteristics and hardware capabilities, but it is expected that new radio access technologies (RATs) will also be deployed. However, existing RATs cannot be replaced completely by the new RATs [1]. Existing wireless networks, such as CDMA (Code Divisional Multiple Access), WCDMA (Wideband Code Divisional Multiple Access), and GSM (Global System for Mobile Communication), will co-exist with newly emerging communication networks. The convergence of heterogeneous networks is difficult to implement in practice. The overall convergence concept demands various sub-projects for its realization. The practical implementation of network convergence remains at the initial phase. However, the leadership in network convergence will be a critical factor determining success in a user-oriented communication environment, especially for smartphone penetration into the mainstream telecommunication market.

Tends in research and development for future network convergence are classified into three major approaches: integrated operation management for multiple networks [2, 3]; efficient unified management of network resources, such as bandwidth or radio spectrum [4, 5]; and development of an intelligent service platform with network/context awareness [6, 7]. Always Best Connected (ABC) [8–11] is one of the prototype methods for network convergence. The impacts of ABC are focused on business optimization based on minimum cost network selection and user satisfaction based on seamless connectivity. The Ambient Network [2, 3] is an open project for network reconfiguration, which includes new standards for network convergence and operation schemes for multi-mode mobile stations. Wireless service operators should build the best service portfolio strategy for each user while maximizing whole network utilization by focusing on maximizing the benefit of network convergence. The best service portfolio strategy provides a competitive advantage in terms of customer satisfaction and effective network utilization also provides an extra opportunity to support the heavy traffic volume caused by growing smartphone services. The Decision Support System (DSS) is one of the best ways of making the service portfolio available to each user in multiple access network environments. Service designers, customer relationship managers, and network engineers can build the best match relationship between services and networks, which enhances user utilization via an easily accessible web-based Decision Support System for building service portfolios.

In this article, we develop a new web-based DSS for building a service portfolio strategy in a network convergence environment. Our major contributions are as follows.

- A new operation framework designed for multiple access networks, which combines services and networks, is applied to the newly developed web-based

DSS as a fundamental methodology. Our proposed operation framework can be applied to access network selection and traffic redistribution. Dynamic network selection and traffic redistribution are an essential part of ABC to guarantee the seamlessness of traffic operations.

- Web-based DSS uses an optimal heterogeneous network operation framework to provide opportunities for designing new services. The network load and financial effect of newly designed services could be analyzed and adapted easily to a given network environment by testing the DSS functionality.
- We propose various mathematical tools for Common Radio Resource Management (CRRM) [12] functions, such as linear programming or marginal cost estimation, to evaluate the effect of newly designed services. The decision-making processes during service deployment include CRRM functions, where the essential component is an estimation of the network effect when deploying services.
- To demonstrate the applicability of our proposed system, we tested various service scenarios in heterogeneous network environments with a range of functions of the web-based DSS.
- Based on an intuitive web user interface, the service scenarios (including various characteristics of each service) and service policies of mobile operators can be built easily and evaluated in a given heterogeneous network environment.
- The proposed overall DSS platform has a fully separated layered structure, which consists of the web presentation server, application server, and network database. This well-designed separated structure guarantees simple maintenance and the application of new features for services or networks (See Fig. 1).

In the next section, we consider related works on network convergence and management in Sect. 2. We then present the DSS software architecture and flow controls in Sect. 3. In Sect. 4, we describe the DSS models and algorithms. Finally,

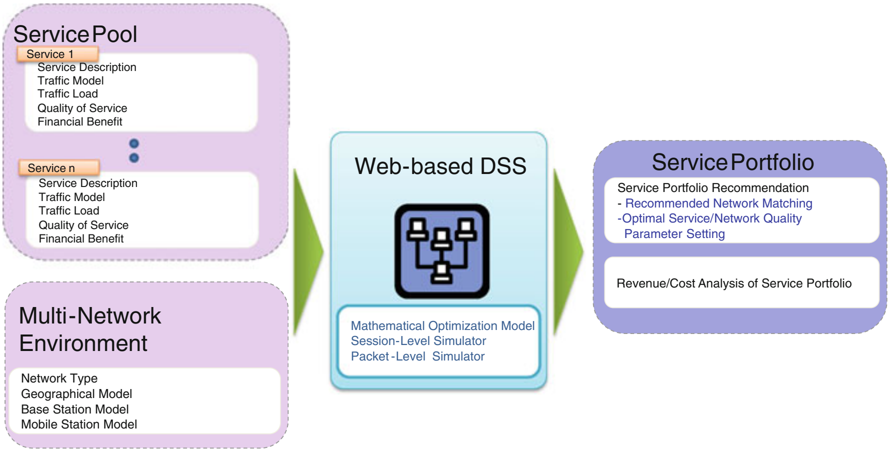


Fig. 1 Service network matching relationship

Sect. 5 presents our practical application and the DSS user interfaces, which are followed by our concluding remarks in Sect. 6.

2 Related Works

Deficiencies in the communication architecture are widely acknowledged during network convergence, so considerable effort is currently being allocated to the development of future network architectures. The study in [13] proposes a type of meta-control plane for future intelligent management of the communication network. The study in [14] proposes the separation of the network into domains or contexts. In these separate contexts, the concept of mapping is used to provide interoperability between heterogeneous networks using different technologies. However, how these mappings can be created between networks remains an unsolved. The dynamic creation of reconfigurable network topologies is the major reason for changing mapping relations. In [15], an abstraction known as a region was proposed as a key architectural design element for extremely large scale and heterogeneous networks. The focus of this study was dynamic interoperability and the creation of common control networks.

The standardization of 3GPP, 3GPP2, and IEEE has investigated the integration of 3G and 2G cellular systems [16, 17], as well as the integration of WLAN (Wireless Local Access Network) and 3G systems [18–21]. Further research studies have investigated the joint resource management of different access technologies [22–28]. Some studies have also considered the sharing of resources between different operators [29, 30]. Newer approaches to multiple network connectivity are based on the ABC concept, e.g., [31–34].

The related studies described above have many limitations. Some earlier studies have focused on two specific radio access technologies that are tightly integrated and that allow joint radio resource management. Clearly, these approaches cannot be extended easily to other radio access technologies. Other previous studies have concentrated on loosely integrated radio access technologies, which comprise a number of radio access technologies. However, these approaches only allow a limited amount of joint resource management, which is usually limited to availability-based access selection with no consideration for rapid variations in the system load or radio link quality variations. Thus, these studies do not fully address the emerging needs of future wireless and ubiquitous networks. Most importantly, previous studies have focused on the adaptation of simple technologies in a heterogeneous network environment. The spread of various services on the smartphone platform has caused variation in the levels of service satisfaction and a huge volume of data traffic. Thus, we need to focus on coordinating the service portfolio strategy and the technically optimized network utilization. The strategic approach to building the user service portfolio rather than network operation optimization might provide significant value in a user-oriented communication environment.

Our proposed DSS approach is broad and general, and it includes all existing/incoming radio access technologies and service combinations. The coordination between various radio access technologies and user services can be supported by various mathematical methodologies. Linear programming, marginal cost function estimation, and packet level simulation can facilitate a strict evaluation of the coordination between networks and services, enabling a focus on business efficiency and operational superiority.

The development of a new web-based DSS for building a service portfolio strategy in a heterogeneous network convergence environment is a totally novel approach. The utility of web-based DSS using an optimal heterogeneous network operation framework provides the best portfolio strategy between services and networks and it has been demonstrated in commercial heterogeneous networks in South Korea. This development and evaluation of a DSS in a commercial network environment is the world's first case study. This system provides open opportunities for designing new services by the testing and applying them promptly in our novel web-based DSS.

3 DSS Software Architecture and Flow

Figure 2 shows the DSS software architecture and flow. According to the user's web interface page activity, the Web Server sends a SOCKET request that could be a mathematical programming optimization request to the Flow Controller (the Flow Controller creates a separate thread to handle the request, where concurrency is supported). After the Flow Controller received the request from the Web Server, it downloads the network and service scenario data set from the Data Management.

The mathematical programming module builds an appropriate mathematical optimization model, such as Linear Programming, before providing the mathematically optimized outputs. The Flow Controller uploads all the mathematical outputs to the Data Management. These mathematically optimized outputs are then displayed via the Web Server using an interactive dialog. If a user wants to test other

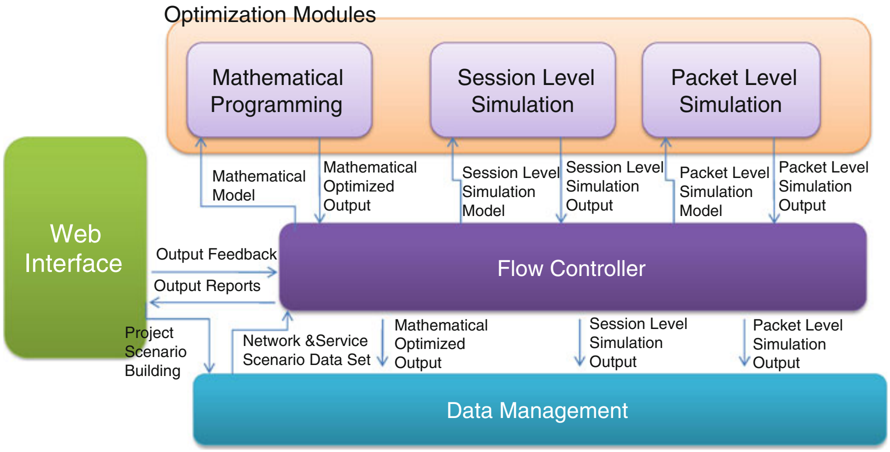


Fig. 2 Software architecture and flow

conditions, the steps above can be iterated until the user has sufficient insight on the outputs. The mathematical programming module can generate a very fast solution as a service portfolio strategy. However, the mathematical outputs only reflect a static snapshot of the service and network status. Therefore, we have a second optimization module, which is a session-level simulation that reflects the dynamic network environment. The Flow Controller initiates a session-level simulation in the session-level simulation module based on user feedback on the mathematical output. The initiation data for the session-level simulator contains the initial resource allocation for each service over each network. Based on the initial resource allocation, the session level simulator generates dynamic service traffic and automatically allocates network resources to each generated service. To guarantee cost-effective allocation of dynamic service traffic, the marginal cost function (see Sect. 4.2.2) is activated in the CRRM element of the session-level simulator. Moreover, the session-level simulation module contains most functions for base stations, mobile stations, and a CRRM element. Each element supports the data processing procedure in the MAC (Media Access Control) layer and higher layer signaling interfaces. The higher layer signaling includes all the requisite upper layers of the MAC layer. The simulator contains the RRC (Radio Resource Control, including RRM), RLC (Radio Link Control), and transport layer (TCP/IP) to simulate multiple access networks. These protocol layers and interfaces are implemented for each network. Note that, the CRRM interworking interface is implemented using the RRC interface of each network.

Figure 3 shows the session-level simulator functional blocks and their interactions. The simulator functional blocks include the mobile station block, network configuration block, protocol blocks, CRRM block, and session management block. The interactions between the functional blocks are performed via the traffic/signaling interfaces of the functional blocks. To achieve the highest effect of CRRM, the updating interval should be the same as the minimum length of the radio frame, i.e., 10 ms for WiMAX, 5 ms for EV-DO, and 10 ms for WCDMA. However, the volume of signaling information is increased by the updating frequency. We set the primary updating interval as 5 s. We verified the suitability of the 5 s interval experimentally. We can apply the packet-level simulation using the finalized outputs of the session-level simulation. The packet-level simulation has precise operations for packet transmission over the networks. Based on the precise traffic and mobility models, the packet-level simulator tracks the overall packet-level behaviors of mobile stations. Over 20 different traffic models based on data from real wireless subscribers (from the networks with >1,700 contents and 6 years of operation) are included in the packet-level simulator. Thus, the packet-level simulator can precisely estimate the network utilization, resource efficiency, and the quality of service at the level of cell, mobile station, and network system. Figure 4 shows the packet-level simulation.

The packet-level simulator can track the entire behavior of networks and mobile stations. However, the simulation time is extremely long (2–3 days for a small network). The DSS provides a user preference option of whether to select packet-level simulation.

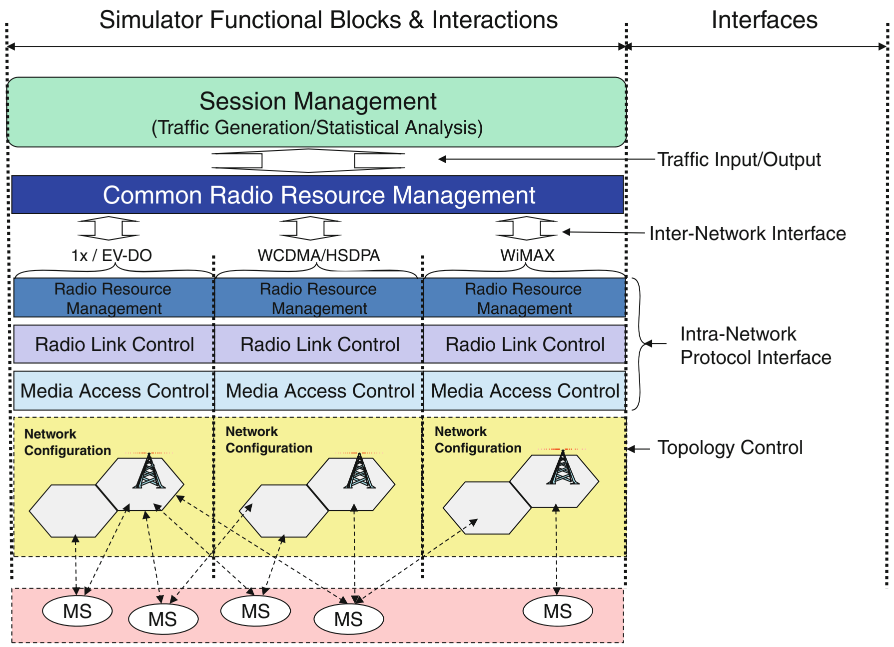
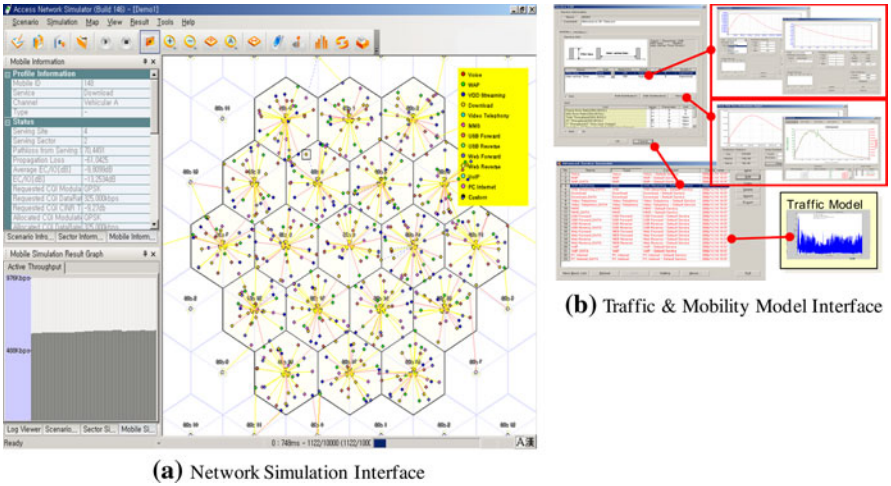


Fig. 3 Architecture of session-level simulator module



(a) Network Simulation Interface

(b) Traffic & Mobility Model Interface

Fig. 4 Screenshot of packet-level simulation

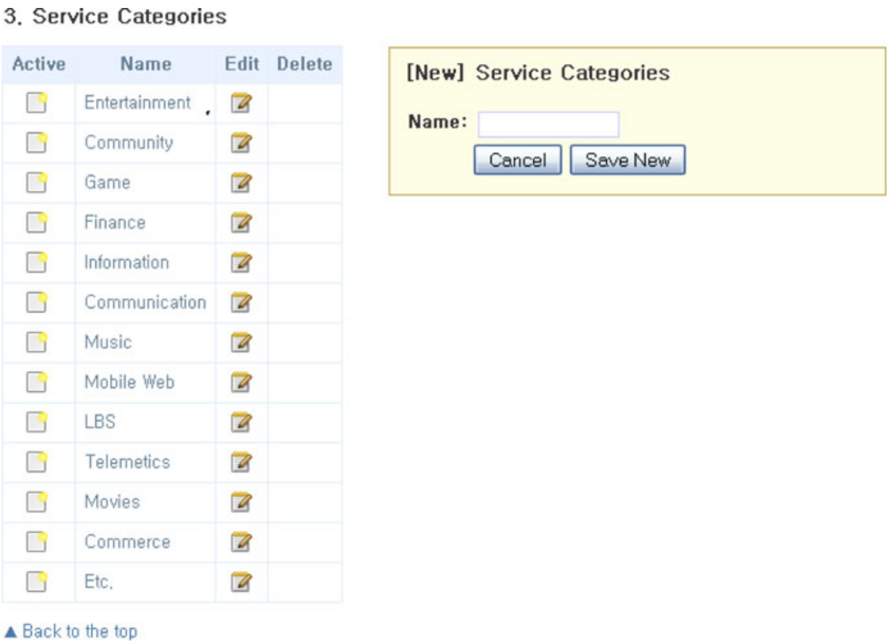
4 Models and Algorithms

4.1 Service and Network Modeling

The developed DSS contains service and network models. In the service model, we initially define the service categories. Based on the practical service applications of service operators, we define 13 categories that encompass all current services: Entertainment, Community, Game, Finance, Information, Communication, Music, Mobile Web, Location Based Service, Telemetics, Movie, Commerce, and Others. Figure 5 shows the 13 categories and the input checkbox in the DSS. We can define an individual service based on the setup of its service category (the service category contains representative service parameters). To define a new service, we first select its service category and then manipulate its detailed parameter values.

The service parameters used by DSS are shown in Table 1. The service session-related data, *session duration,* and *session inter-arrival time* can be defined using a range of distribution models. We provide representative probabilistic models for the session duration and inter-arrival time. These models can be selected easily in DSS. Furthermore, we provide sample models for selected services. The sample models are based on the traffic analysis of commercial network operations [35], which also include the aggregated traffic volume of the service (*traffic load*) and the service user count (*subscriber*). The *Benefit* indicates the total profit earned for each service, which can be set as a dollar amount per kilobit. DSS uses the Net Present Value (NPV) method to calculate the total profit. *Mobile Station* indicates the types of mobile devices and their distribution, which support the service. *High-end* is defined as all devices that were available after 2007 and priced >$500, whereas other devices are considered *Low-end*. The basic distribution of devices was obtained based on device information from a commercial network operator in Korea.

Figure 6 shows the input box for the service parameters.



3. Service Categories

Active	Name	Edit	Delete
☐	Entertainment	✎	
☐	Community	✎	
☐	Game	✎	
☐	Finance	✎	
☐	Information	✎	
☐	Communication	✎	
☐	Music	✎	
☐	Mobile Web	✎	
☐	LBS	✎	
☐	Telemetics	✎	
☐	Movies	✎	
☐	Commerce	✎	
☐	Etc.	✎	

[New] Service Categories

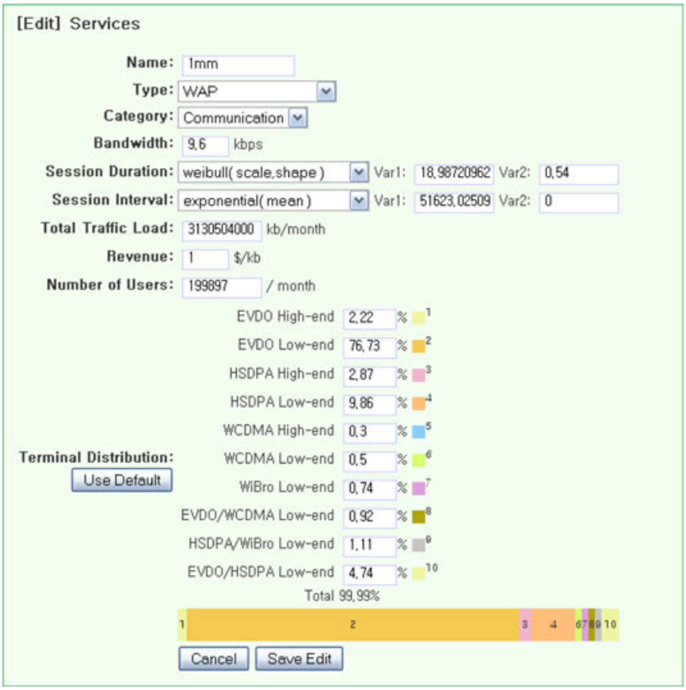
Name:

Fig. 5 Service category setup

Table 1 Service parameters

Name	Description	Option
Session duration	Probabilistic model for the period of continuous data transmission	Uniform (a, b) Poisson (mean) Normal (mean, sigma) Lognormal (mean, sigma) Exponential (mean) Constant (c) Binomial (mean, N) Bernoulli (mean) Weibull (scale, shape)
Session inter-arrival	Probabilistic model for the time between one session and the other session	Uniform (a, b) Poisson (mean) Normal (mean, sigma) Lognormal (mean, sigma) Exponential (mean) Constant (c) Binomial (mean, N) Bernoulli (mean) Weibull (scale, shape)
Traffic load	Generated traffic volume counted as (Kbits/month)	
Benefit	Total financial benefit of the service counted as ($/Kbits)	
Subscriber	The number of subscribers to the service	
Mobile station	Probabilistic model for mobile stations that support the service.	Single mode mobile station EV-DO high-end/EV-DO low-end HSDPA high-end/HSDPA low-end WCDMA high-end/WCDMA low-end WiBro low-end Dual mode mobile station EV-DO/WCDMA low-end HSDPA/WiBro low-end EV-DO/HSDPA low-end

Five types of base stations were used to set up the network environment: CDMA 1x, EV-DO, WCDMA-only, WCDMA/HSDPA, and WiMAX. Each base station in the network environment has parameters such as the network type, maximum capacity, peak-to-average capacity ratio, service coverage, access cost function, and CRRM availability. The maximum capacity denotes the peak data rate of a base station on a given network type while the peak-to-average capacity ratio is used to measure the practical cell throughput (the cell throughput is a single cell's total transmissible bits per second for user services). Given that the PF scheduling algorithm provides a peak data rate of 21.1 Mbps to 20 active users in HSDPA, the median user throughput is about 350 kbps [36]. To reproduce this effect, DSS provides a parameter, i.e., the peak to median capacity ratio, which sets the ratio



Name: 1mm
Type: WAP
Category: Communication
Bandwidth: 9,6 kbps
Session Duration: weibull(scale,shape) Var1: 18,98720962 Var2: 0,54
Session Interval: exponential(mean) Var1: 51623,02509 Var2: 0
Total Traffic Load: 3130504000 kb/month
Revenue: 1 $/kb
Number of Users: 199897 / month

Terminal Distribution:

EVDO High-end	2,22 %	1
EVDO Low-end	76,73 %	2
HSDPA High-end	2,87 %	3
HSDPA Low-end	9,86 %	4
WCDMA High-end	0,3 %	5
WCDMA Low-end	0,5 %	6
WiBro Low-end	0,74 %	7
EVDO/WCDMA Low-end	0,92 %	8
HSDPA/WiBro Low-end	1,11 %	9
EVDO/HSDPA Low-end	4,74 %	10

Total 99,99%

Fig. 6 Service parameter setup

between the peak and median data rate. The access cost function of a cell is the marginal cost function for accessing a cell (see Sect. 4.2). On/Off CRRM availability can be selected for each base station. Note that CDMA 1x and WCDMA-only support real-time traffic only whereas EV-DO and WiMAX support non-real-time traffic (non-real-time traffic does not require time-sensitive transmission, e.g., file downloading and e-mail). The WCDMA/HSDPA supports real-time and non-real-time traffic, where real-time traffic is supported by the non-HSDPA component while non-real-time traffic is supported by the HSDPA component. The capacity of HSDPA is dynamically adjusted based on the amount of real-time traffic that has to be accommodated. The service coverage should determine the shape of each cell. In practice, the cell shape cannot be hexagonal because it depends on many environmental factors, such as the topology of the area where the base station is located, buildings, moving objects, and even weather situation. DSS allows users to generate a random cell shape. The cell shape can also be adjusted manually. Figure 7 shows the network setup interface in DSS.

4.2 Network Management Algorithms

Two essential network management algorithms are included in DSS to produce an optimal service portfolio strategy. Mathematical programming estimates the load generated for each service and it allocates an appropriate network given load-balancing constraints. Policy-based market driven network selection and traffic

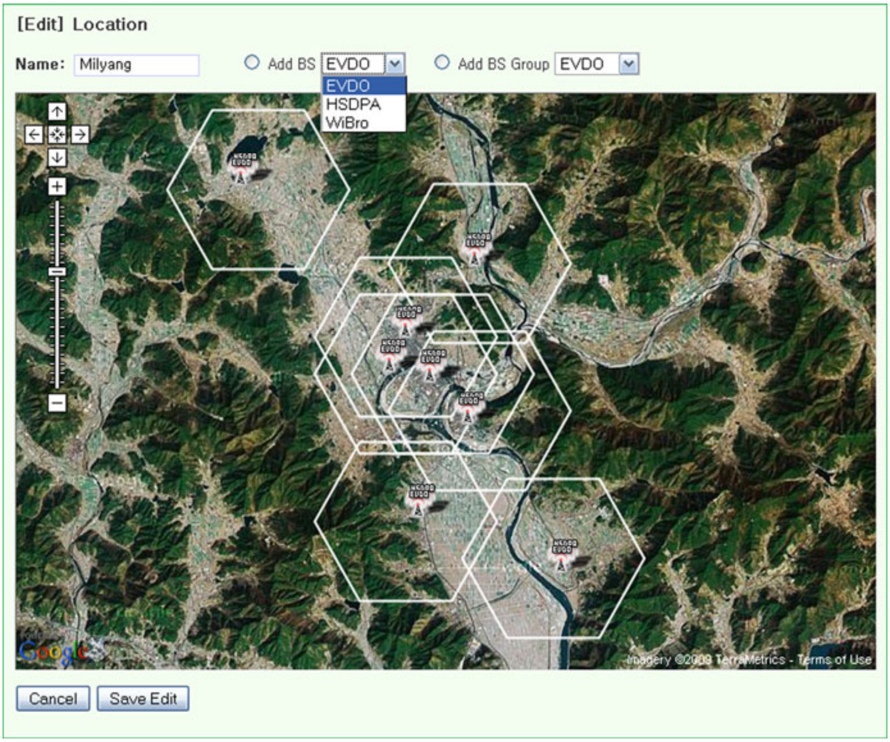


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Fig. 7 Network setup interface

redistribution algorithms are used for the dynamic distribution of service traffic in the session-level and packet-level simulation modules.

4.2.1 Mathematical Programming

Mathematical programming is used to build the initial service portfolio strategy. Linear programming (LP) is used to evaluate the network load and financial effect of newly designed services. The main objective of LP is load balancing among networks. The loads can be estimated each day, week, and month. These aggregated loads provide a snapshot of the given network status. The LP provides a mathematically optimized output (service portfolio strategy) for the snapshot based on aggregated load balancing. The session-level simulator and packet-level simulator use the output from the LP as an initial solution to build the finalized service portfolio strategy in a dynamic environment (in dynamic environment, the calls are generated and move as described in the service parameters shown in Table 1 for the service test scenario shown in Table 2). The input factors for LP are as follows: (1) estimated aggregated load for each service, (2) network structure and network capacity, and (3) network availability for each service. The output generated from LP contains: (1) the load allocated to each network for each service and (2) load balancing information among networks.

Table 2 Service test scenario

Descriptor	Description
Simulation time	Total simulation time for the service test scenario.
Time band	Practical time band such as, Morning, Afternoon, and Evening. The volume of traffic varies according to the time band.
Test region	Geographical region for test scenario. The Google map is displayed to visualize test region. The demographic of base stations is supported.
Traffic fraction of test region	The ratio of traffic volume generated in the test region compared with national wide traffic generation. For example, the generated traffic volume of test region is 3.5 % of national wide traffic generation.
Service combination set	List of services in the test scenario. Each service is defined by the service editing function.
Traffic model	Probabilistic models of Services in the test scenario. The list of models is presented in Table 1.

4.2.1.1 LP Formulation Let n denote the number of networks and assume that the amount of traffic is denoted by the number of bits per second. For each service i, there are n decision variables $x_{i,1}$, $x_{i,2}$, …, $x_{i,n}$, where $x_{i,j}$ denotes the amount of traffic from service i allocated to network j. The total traffic amount T_i of traffic from service i distributed among n networks is then $\sum_j x_{i,j} = T_i$ (*constraint* 1). When there are multiple options for providing service i with different QoS metrics (e.g., video streaming service with 128 or 512 kbps), service i can be supported by multiple transmission channels with different traffic volumes. Thus, we include two additional constraints for each service i, $T_i = \sum_k d_{i,k} t_{i,k}$ (*constraint* 2) and $\sum_k d_{i,k} = 1$ (*constraint* 3). Let $t_{i,k}$ denote the maximum volume using the k th transmission channel and $d_{i,k}$ be a binary decision variable used to determine the transmission channel selected for service i, assuming that only one channel can be selected for each i. The capacity C_j constraint in each network j is denoted as $\sum_i x_{i,j} \le C_j$ (*constraint* 4) while the ratio of network j's load over its capacity is denoted as $L_j = \frac{1}{C_j} \sum_i x_{i,j}$. To facilitate load balancing when formulating an objective function, we introduce two additional decision variables m and M such that $m \le L_j \le M$ for each network j (*constraint* 5). Thus, m and M are the bounds of the network load. The preferred maximum network load is usually assumed to be 0.7–0.8 [36]. Thus, the constant M should be set to the preferred maximum value within the appropriate range for the network load. In contrast, the constant m could be set as an arbitrary number less than the maximum load, including zero.

The objective function $obj = c_1(M - m) + c_2 M$ is then formulated using *constraints* 1–5 where two weight factors c_1 and c_2 are not decision variables. Instead, they are used as input parameters that reflect the desired optimization goal. For example, if the primary goal is load balancing, we set $c_1 = 1$ and $c_2 = 0$, and try to minimize obj_1. If minimizing the maximum load among networks is the primary goal, we set $c_1 = 0$ and $c_2 = 1$. Appropriate values of c_1 and c_2 should be determined using experiments based on the optimization goal.

We now consider the case when additional network usage policies exist for determining how traffic from each service should be distributed among networks. If strict lower and upper bounds $\alpha_{i,j}$ and $\beta_{i,j}$ exist on $x_{i,j}/T_i$ (i.e., the ratio of service i's load on network j over the service i's total traffic amount), we add the new constraints $\alpha_{i,j}T_i \leq x_{i,j} \leq \beta_{i,j}T_i$ to each service i and network j (*constraint* 6). If no desired lower or upper bounds exist, we set $\alpha_{i,j} = 0$ and $\beta_{i,j} = 1$.

4.2.1.2 Two Sets of LP Optimizations Based on the aforementioned LP formulation, we provide two sets of mathematical optimizations as follows.

Set 1 (*Multi-Network Solution*) For existing services and newly designed services, we maintain the lower bounds and upper bounds as the LP constraints. The lower and upper bound for a given service represent the allocation bounds of traffic load for the service on each network (see *constraint* 5 in LP). Next, we generate the solution for a multi-access network. In this scenario, we can have a solution where good load balancing is achieved in the multi-access network.

Set 2 (*Single Network Solutions*) In order to check the load when new services are supported by only one network in the multi-network environment, LP is carried out n times for each n network. At each time, the lower and upper bound remain unchanged for existing services. For newly designed services, the upper bound is set as 1 for one network and 0 for all other networks. For example, if there are three networks {EV-DO, HSDPA, WiMAX} and a new service i, the lower and upper bounds are given as ($\alpha_{i,\mathrm{EVDO}} = 0$, $\beta_{i,\mathrm{EVDO}} = 1$), ($\alpha_{i,\mathrm{HSDPA}} = 0$, $\beta_{i,\mathrm{HSDPA}} = 0$), and ($\alpha_{i,\mathrm{WiMAX}} = 0$, $\beta_{i,\mathrm{WiMAX}} = 0$) for the EV-DO network solution.

In this scenario, we can have single network solutions where the new services are allocated to a single network and load balancing is achieved within a multi-access network. Thus, we can check the effects on different networks of different service allocations.

All possible solutions are displayed after the mathematical modeling module of DSS is executed. For each solution, the summary results show the load increment for each network, increment of network usage ratio, financial benefit of services, and additional cost.

4.2.1.3 Remarks Our LP model implemented in DSS can be extended to as multi-stage LP model, which can incorporate additional network usage policies. Suppose there exists a desirable, but not necessarily strict, bound $p_{i,j}$ on $x_{i,j}/T_i$. In contrast to the lower and upper bounds $\alpha_{i,j}$ and $\beta_{i,j}$ in *constraint* 6, $p_{i,j}$ is only a desired bound and it may not always be achievable. Therefore, we should try to minimize the difference between $x_{i,j}$ and $p_{i,j}T_i$ by adding two decision variables $u_{i,j}$ and $v_{i,j}$ for each i and j such that $x_{i,j} - p_{i,j}T_i = u_{i,j} - v_{i,j}$ where $u_{i,j} \geq 0$ and $v_{i,j} \geq 0$ (*constraint* 7). We can formulate a second objective function $obj_2 = c_3 \sum_{i,j} (u_{i,j} + v_{i,j})$, where c_3 is a user-defined weight factor. The final objective function is then formulated as $obj = obj_1 + obj_2$ with the objective of minimizing obj under *constraints* 1–7.

Using these multiple objective functions, the multi-stage LP model can be designed using the following two step optimization method.

Step 1: Finding an optimized output using only the first objective function obj_1 under *constraints* 1–6. Let $\tilde{M}$ and $\tilde{m}$ denote the output value when minimizing obj_1.

Step 2: Finding an optimized output using only the second objective function obj_2 under *constraints* 1–7 and $(\tilde{M} - \tilde{m}) - \varepsilon \leq (M - m) \leq (\tilde{M} - \tilde{m}) + \varepsilon$ (*constraint relaxation bound* ε)

4.2.2 Policy-Based Market-Driven Network Selection and Traffic Redistribution

Policy-based market-driven network selection and traffic re-distribution are used to guarantee load balancing at the cell level by session-level and packet-level simulators. During appropriate network evaluations, we build an effective operational policy for heterogeneous network environments.

The fundamental design objective of the operational policy in heterogeneous networks is to minimize the additional "costs" that result from deviations from various operational policies, including load balancing in heterogeneous networks. Thus, we assign a positive function to the traffic load, which is known as a marginal cost function, for each cell in the networks. The value of the marginal cost function for a given load on the cell can be interpreted as the additional cost incurred when utilizing one more unit of the remaining traffic resource in the cell. When we consider that the capacity of each cell is limited and that the market principle ensures resources become expensive with scarcity, we can assume that the marginal cost function for each cell is increasing. A simple way of defining a marginal cost function for the cell is to use an increasing function (see Fig. 8).

The accumulated cost due to traffic load u for a cell can be calculated by integrating the corresponding marginal cost function from 0 to u. If we have N cells B_1, …, B_N, which are provided with the marginal cost functions f_1, …, f_N, respectively, the total accumulated cost T for all the cells at traffic distribution (u_1, u_2, …, u_N) is given by

$$T(u_1, u_2, \ldots, u_N) = \int_0^{u_1} f_1(u)du + \cdots + \int_0^{u_N} f_N(u)du \tag{1}$$

where f_i is the marginal cost function associated with the cell B_i and u_i is the current load taken by the cell B_i ($i = 1, \ldots, N$). Thus, the minimum of the total accumulated cost T is achieved at an equilibrium state $\left(u_1^*, \ldots, u_N^*\right)$, which satisfies the following equation:

$$f_1\left(u_1^*\right) = f_2\left(u_2^*\right) = \ldots = f_N\left(u_N^*\right) \tag{2}$$

where it is assumed that $u_1 > 0$, …, $u_N > 0$, and the total amount of traffic is constant over time (see Appendix 1 for a proof). At equilibrium states, any change in traffic distribution always produces an additional cost.

The above result provides an insight into adjusting the traffic distribution dynamically in heterogeneous networks. To develop a dynamical model for

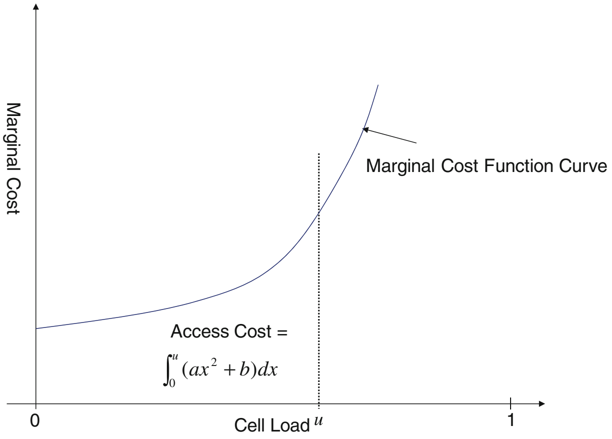


Fig. 8 Example of the marginal cost function

adjusting the traffic distribution, let $G = (B, C)$ be a connected graph of N cells in the heterogeneous networks, where $B = \{B_i\}_{i=1,\ \ldots,\ N}$ represents the set of N cells and $C = (c_{ij})$ is the corresponding adjacency matrix with

$$c_{ij} = \begin{cases} 1, & \text{if cell}\, B_i \text{ is a neighbor of cell } B_j \\ 0, & \text{otherwise.} \end{cases} \quad (i,j = 1,\ldots,N) \tag{3}$$

A neighborhood relationship between two cells implies that traffic can transit between them. Our traffic transition strategy requires that the marginal cost in cell B_i is greater than the average of the marginal costs of all neighboring cells. Thus, traffic transits dynamically from cell B_i to neighboring cells so the differences in the marginal costs among cells are gradually diminished. The nonlinear system of autonomous differential equations embodies the following traffic transition strategy:

$$\begin{aligned} \frac{du_1}{dt} &= -\lambda \sum_{j=1}^{N} c_{1j}(f_1(u_j) - f_j(u_j)) \\ \frac{du_2}{dt} &= -\lambda \sum_{j=1}^{N} c_{2j}(f_2(u_j) - f_j(u_j)) \\ &\vdots \\ \frac{du_N}{dt} &= -\lambda \sum_{j=1}^{N} c_{Nj}(f_N(u_j) - f_j(u_j)) \end{aligned} \tag{4}$$

where λ is a fixed transition rate and the traffic conservation of the system is assumed. The dynamical system has a unique equilibrium. By letting $\dot{u}_1 = \ldots = \dot{u}_N = 0$, we obtain a system of equations for $(u_1,\ldots,u_N)$ as $f_1(u_1) = f_2(u_2) = \ldots = f_N(u_N)$, which has a unique solution $(u_1^*, \ldots, u_N^*)$, because each function f_i $(i = 1, \ldots, N)$ is strictly increasing and the total traffic $u_1 + \cdots + u_N$ is constant over time. To determine whether the traffic distribution state $u_1, \ldots, u_N$

actually converges to the equilibrium state $\left(u_1^*, \ldots, u_N^*\right)$, we introduce a non-negative scalar function V for time t defined by the following equation

$$V(t) = \sum_{i,j} c_{ij}(f_i(u_i(t)) - f_j(u_j(t)))^2 \tag{5}$$

The function V can be considered to be a function for measuring the "variation" in marginal costs among the cells at time t. Its value indicates how well-balanced the traffic distribution is and $V(t) = 0$ implies that the system has arrived at an equilibrium state at time t. We can show that, assuming the dynamical system (4), the value $V(t)$ converges to zero as the time approached infinity, showing that $u_1, \ldots, u_N$ converges to an equilibrium state $(u_1^*, \ldots, u_N^*)$ (see Appendix 2 for a proof).

The corresponding current marginal cost has been calculated for the neighboring cells B_1, B_2, B_3 and B_4. The red solid arrows indicate the directions of traffic transition among neighboring cells, according to the traffic transition strategy (Fig. 9).

We then construct a practical operation framework that consists of an access network selection method and a traffic redistribution scheme, which is based on a mathematical analysis of the marginal cost function. The marginal cost function includes load balancing and additional policies for service operators, such as call priority handling. Load balancing is the main objective of access selection and traffic redistribution, although load balancing should be operated with the restriction of priority handling among cells. The priority handling is dealt with by the following marginal functions.

To demonstrate the practical applicability of the policy-based marginal cost function, we define two types of services in CDMA 1x, EV-DO, WCDMA-only, WCDMA/HSDPA, and WiMAX cells. The real-time traffic has a higher priority than non-real-time traffic (new real-time traffic may be admitted to a non-HSDPA component of the WCDMA/HSDPA by dropping or redirecting existing data traffic in the HSDPA component). Next, we build a single operation framework for real-time and non-real-time traffic in heterogeneous network environments. We define a

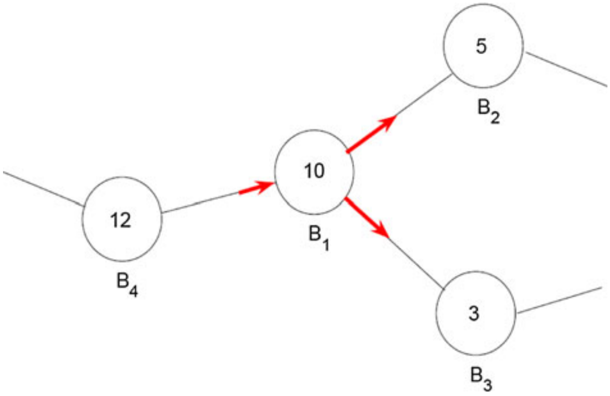
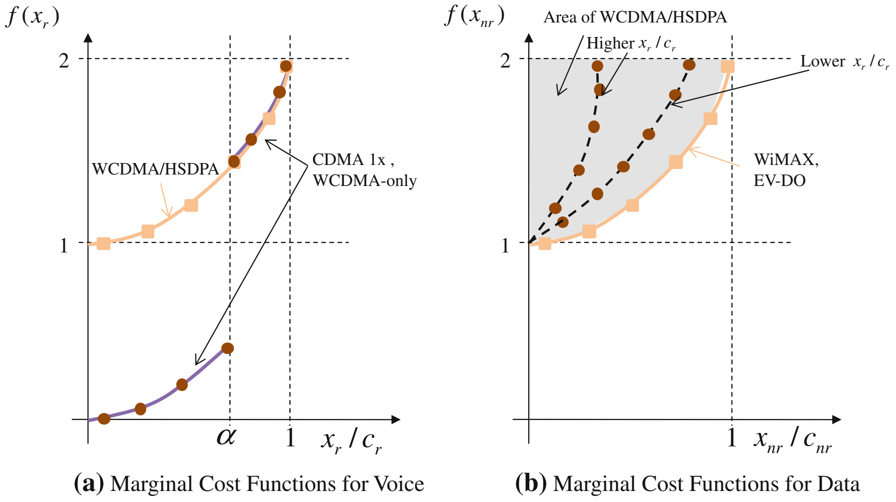


Fig. 9 Traffic transition

marginal cost function for each RAT and assign a marginal cost value to each of its cells. The whole set of following marginal cost functions acts as the core of the operation framework where CDMA 1x and WCDMA-only cells are preferable for real-time traffic while the capacity of the WCDMA/HSDPA cells is reserved for arriving non-real-time traffic, thereby minimizing the total load. Note that the following marginal function is used for each network during the practical implementation described above for $f_i(u_i)$.

1. For CDMA 1x, $f_r(x_v) = \begin{cases} (x_r/c_r)^2 & \text{if } x_r/c_r < \alpha \\ (x_r/c_r)^2 + 1 & \text{otherwise} \end{cases}$
   where x_r and c_r denote the load and total capacity of CDMA 1x cell r. The marginal cost of CDMA1x is maintained at a lower level by the condition $(x_r/c_r < \alpha)$, which ensures that the resources of CDMA 1x are assigned preferentially to real-time traffic.
2. For WCDMA-only, $f_r(x_v) = \begin{cases} (x_r/c_r)^2 & \text{if } x_r/c_r < \alpha \\ (x_r/c_r)^2 + 1 & \text{otherwise} \end{cases}$
   where x_r and c_r denote the load and total capacity of WCDMA-only cell r. The effect of α is similar to that with CDMA 1x.
3. For EV-DO, $f_{nr}(x_{nr}) = (x_{nr}/c_{nr})^2 + 1$
   where x_{nr} and c_{nr} denote the load and the total capacity of EV-DO cell nr.
4. For WCDMA/HSDPA, $\begin{aligned} f_{nr}(x_r, x_{nr}) &= (x_{nr}/c_{nr})^2/(1 - x_r/c_r)^2 + 1 \\ f_r(x_r) &= (x_r/c_r)^2 + 1 \end{aligned}$
   where x_r and c_r (x_{nr} and c_{nr} respectively) denote the load and total capacity of the non-HSDPA component r of WCDMA/HSDPA cell (HSDPA component nr of WCDMA/HSDPA cell).
5. For WiMAX, $f_{nr}(x_{nr}) = (x_{nr}/c_{nr})^2 + 1$
   where x_{nr} and c_{nr} denote the load and total capacity of WiMAX cell nr.

Figure 10 shows the functional behavior of the above marginal cost functions. When (x_r/c_r) is less than α, the marginal cost of WCDMA-only or CDMA 1x is lower than the value of the non-HSDPA component of WCDMA/HSDPA. Thus, the real-time traffic is allocated to the WCDMA-only or CDMA 1x cells. However, when (x_r/c_r) is higher than α, the marginal cost of the non-HSDPA component of WCDMA/HSDPA has the same level as WCDMA-only or CDMA 1x. Thus, the real-time traffic is allocated among WCDMA-only, CDMA 1x, or the non-HSDPA component of WCDMA/HSDPA. The non-real-time traffic allocation of the HSDPA component of WCDMA/HSDPA is determined by (x_r/c_r) for the non-HSDPA component of WCDMA/HSDPA. If (x_r/c_r) is at a lower level, the marginal cost of the HSDPA component of WCDMA/HSDPA has a similar value to EV-DO or WiMAX. However, If (x_r/c_r) is higher, the marginal cost of the HSDPA component of WCDMA/HSDPA increases more rapidly than that of EV-DO or WiMAX. Thus, the use of the HSDPA component of WCDMA/HSDPA is managed strictly for the incoming real-time traffic of WCDMA/HSDPA.



(a) Marginal Cost Functions for Voice **(b)** Marginal Cost Functions for Data

Fig. 10 Functional behavior of the marginal cost function

Based on the proposed marginal cost function, we now introduce an operation framework that consists of an access network selection method and a traffic redistribution scheme. Each cell reports the current load to the CRRM module periodically or in an event-driven manner (i.e., based on report requests from the CRRM module). CRRM then estimates the marginal cost of each cell. The access network selection process is initiated by a connection request from a mobile station. The CRRM selects a cell with a minimum marginal cost and directs the mobile station to the selected cell. The traffic redistribution process is more complex. During each fixed time interval, the marginal cost for each cell is updated by the CRRM. The CRRM then guides the mobile stations to perform handovers.

Note that the main assumption of this model is a uniform measurement of load for each network. We set the cell load, which is referred to as percentages, as the measurable value for each cell. We then build marginal cost functions to maintain the cell load balance. We also assume free traffic redistribution among networks. Based on an estimation of the marginal cost for each network, traffic can move from one cell to another cell without any limitations. The load and utilization have the same measurable values and the only difference between them is the point of view. The load is used when considering the network resource consumption by network operators while utilization is considered to determine profit generation for customers.

Figure 11 shows the overall structure of the models and algorithms described in Sect. 4.

5 Practical Applications

We provided a practical demonstration of service portfolio building and network impact analysis. After running DSS, we can observe the financial and network-wide impact of a newly introduced service on a multi-access network environment.

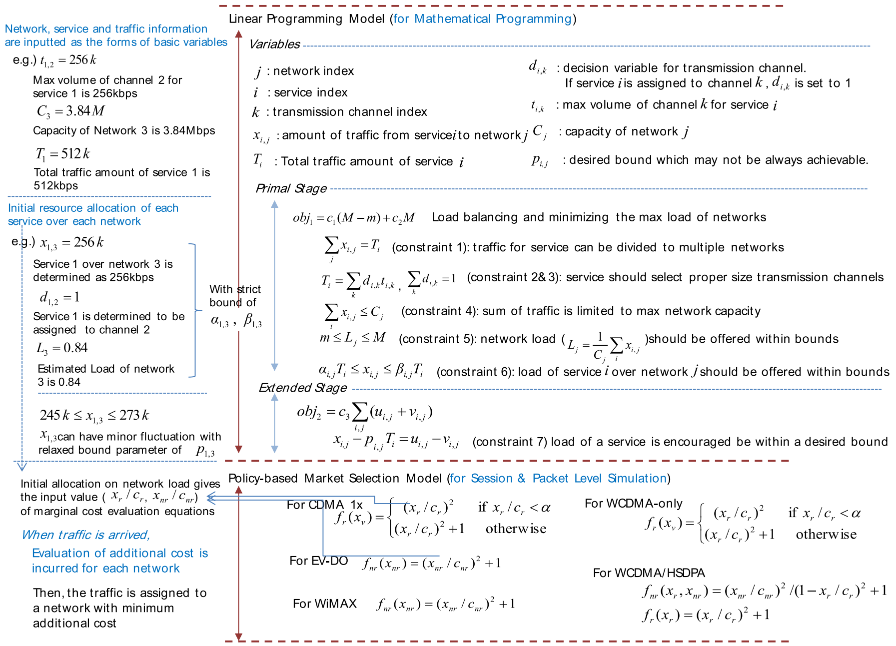


Fig. 11 Overall structure of the models and algorithms

5.1 Service Test Scenario

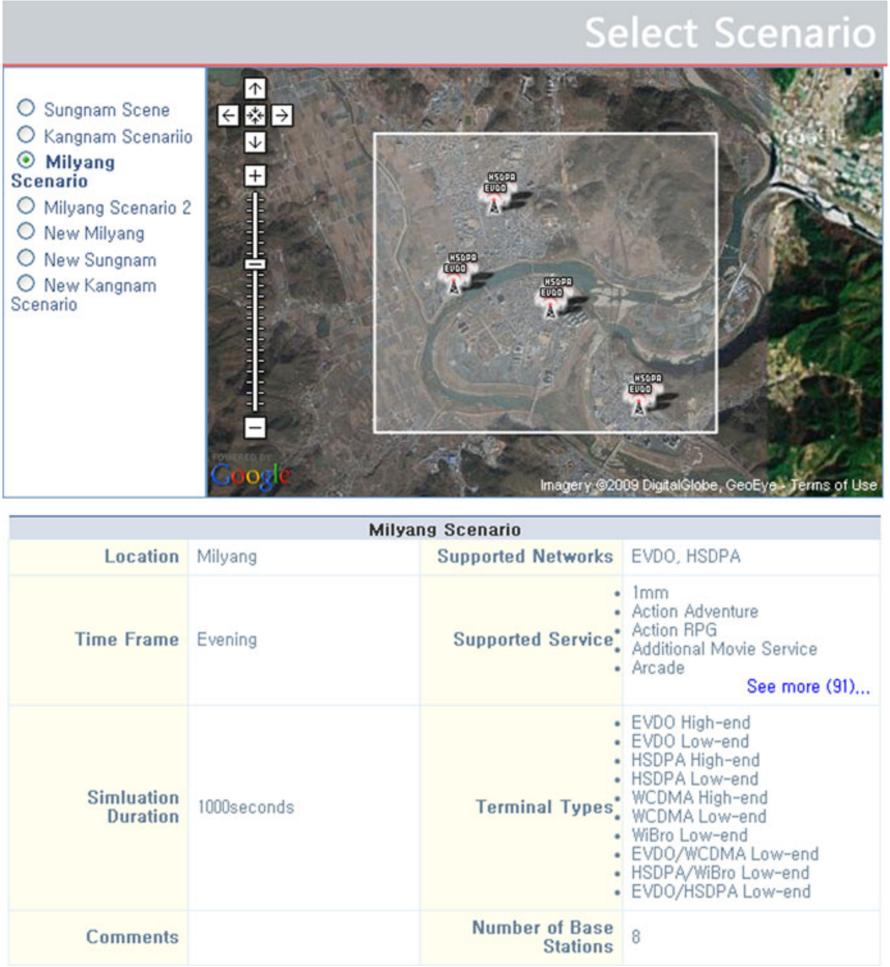
First, we initialize the simulator environment. Using the scenario manager, we can define the physical properties of the network and determine a list of services present in the network, as shown in Fig. 12.

The service test scenario consists of the test simulation time, time band, test region, service combination set, and traffic models of the service combination set. Table 2 shows the setup of the service test scenario.

5.2 Adding New Services

When the preliminary settings have been completed, a project is created to add new services to the scenario and run them using a simulation. Figure 13 shows the addition of two new services (Service1 and Service2) to an existing scenario. We can specify the service type, various cost factors (such as, terminal, marketing, and customer support costs), the target number of subscribers, and the requisite terminal penetration of the new services. This creates a new environment where the impact of new services and the cost/profit analysis can be evaluated.

As shown in Fig. 14, the distribution of services over the network is then specified. The distribution of mobile devices and existing services are presented alongside the interface. These values are used to set the lower and upper bounds for each network as the policy constraint described in Sect. 4.2.1.



Select Scenario

○ Sungnam Scene
○ Kangnam Scenariio
● **Milyang Scenario**
○ Milyang Scenario 2
○ New Milyang
○ New Sungnam
○ New Kangnam Scenario

Milyang Scenario

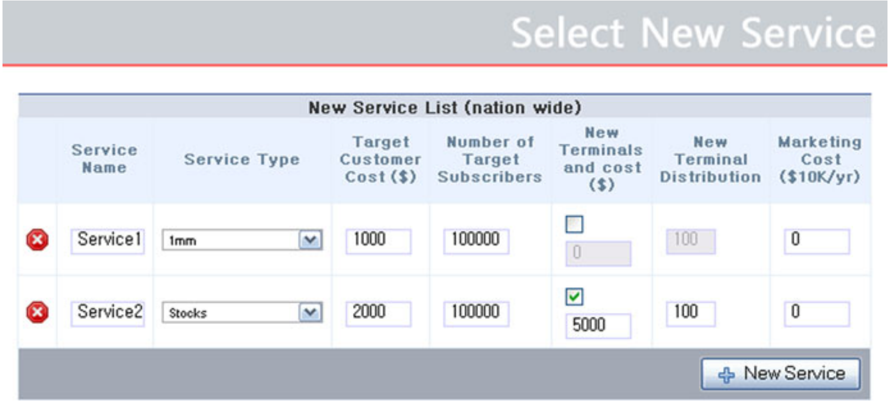
Location	Milyang	**Supported Networks**	EVDO, HSDPA
Time Frame	Evening	**Supported Service**	• 1mm • Action Adventure • Action RPG • Additional Movie Service • Arcade See more (91)...
Simluation Duration	1000seconds	**Terminal Types**	• EVDO High-end • EVDO Low-end • HSDPA High-end • HSDPA Low-end • WCDMA High-end • WCDMA Low-end • WiBro Low-end • EVDO/WCDMA Low-end • HSDPA/WiBro Low-end • EVDO/HSDPA Low-end
Comments		**Number of Base Stations**	8

Fig. 12 Service test scenario

5.3 An Exemplar of Simulation Results

Once the project has been configured completely, DSS provides initial results based on the mathematical programming module described in chapter 3 and the final results of the session-level simulation.

The initial results can provide multi-network scenario and single-network scenario results. They are based on the project configuration and two sets of mathematical optimizations from Sect. 4.2.1 for new services in a multi-network and single network environment. The user has the choice of two different views of the effect of the new service in the final simulation. In our example simulation results, we used the mathematical optimization model. The basic model described in Sect. 4.2 is used to determine the initial mathematical solution by simply adding the

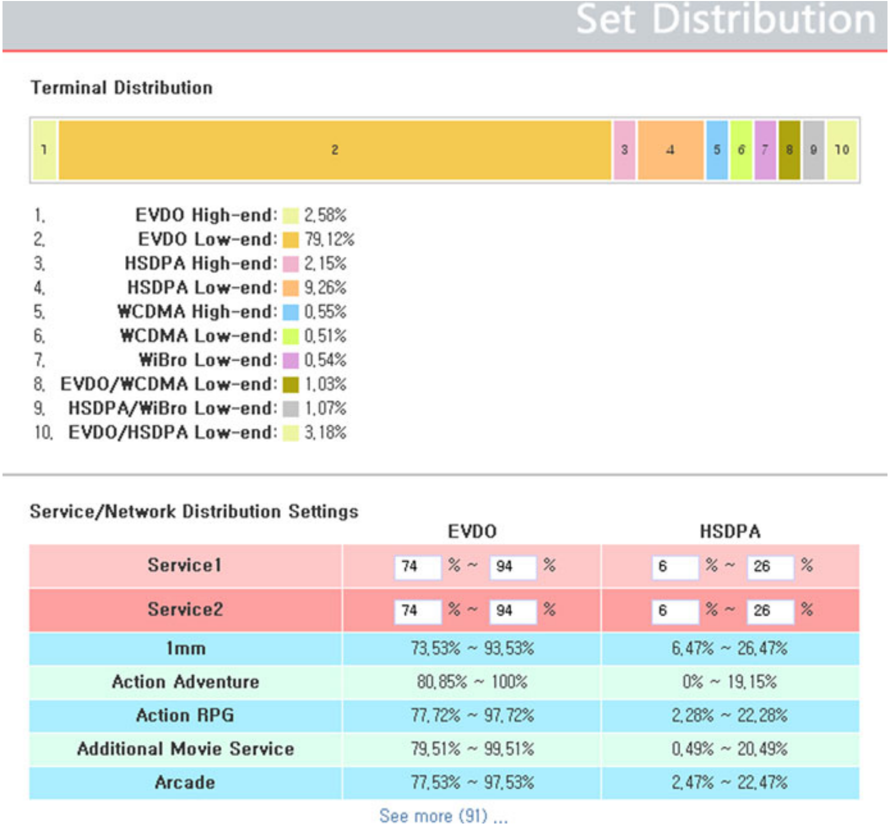


Select New Service

New Service List (nation wide)

	Service Name	Service Type	Target Customer Cost ($)	Number of Target Subscribers	New Terminals and cost ($)	New Terminal Distribution	Marketing Cost ($10K/yr)
☒	Service1	1mm	1000	100000	☐ 0	100	0
☒	Service2	Stocks	2000	100000	☑ 5000	100	0

Fig. 13 New service creation



Set Distribution

Terminal Distribution

1. EVDO High-end: ■ 2.58%
2. EVDO Low-end: ■ 79.12%
3. HSDPA High-end: ■ 2.15%
4. HSDPA Low-end: ■ 9.26%
5. WCDMA High-end: ■ 0.55%
6. WCDMA Low-end: ■ 0.51%
7. WiBro Low-end: ■ 0.54%
8. EVDO/WCDMA Low-end: ■ 1.03%
9. HSDPA/WiBro Low-end: ■ 1.07%
10. EVDO/HSDPA Low-end: ■ 3.18%

Service/Network Distribution Settings

	EVDO	HSDPA
Service1	74 % ~ 94 %	6 % ~ 26 %
Service2	74 % ~ 94 %	6 % ~ 26 %
1mm	73.53% ~ 93.53%	6.47% ~ 26.47%
Action Adventure	80.85% ~ 100%	0% ~ 19.15%
Action RPG	77.72% ~ 97.72%	2.28% ~ 22.28%
Additional Movie Service	79.51% ~ 99.51%	0.49% ~ 20.49%
Arcade	77.53% ~ 97.53%	2.47% ~ 22.47%

Fig. 14 Distribution of services over networks

new variables ($x_{i,j}$), which denote new services. In the revised model, the total load limitation (*constraint* 1) should be maintained for the newly introduced services. Channel type choice constraints (*constraint* 2 and *constraint* 3) and a network load limitation constraint (*constraint* 4) should also be applied to newly introduced services. Thus, we can build the final revised optimization model with simple modified constraints and added variables.

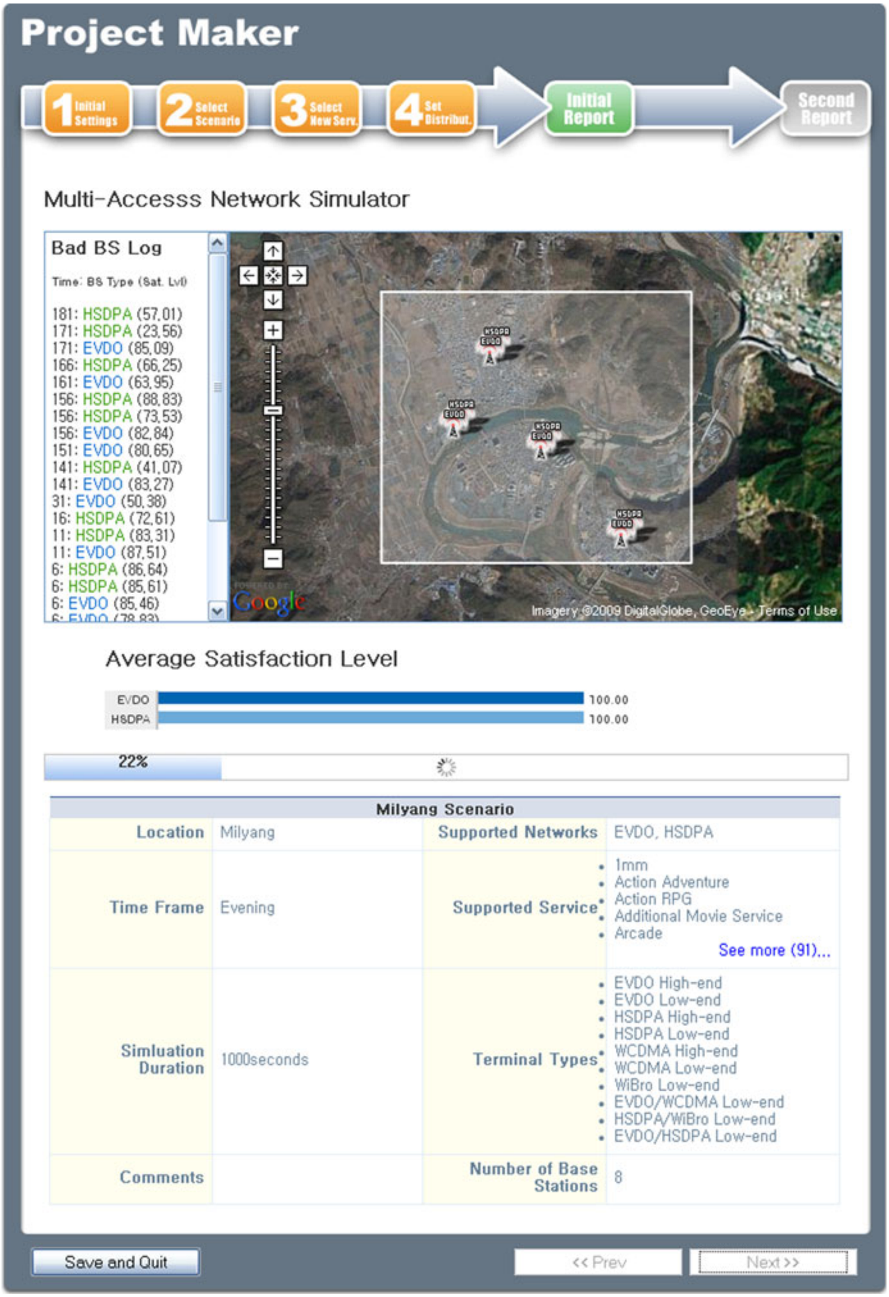
While the session-level simulation is being performed, an interface provides the user with the satisfaction level, as shown in Fig. 15. The satisfaction level is defined as (Assigned Bandwidth/Bandwidth Requirement) × 100, while all base stations that fall below a 90 % satisfaction level are displayed in the list on the left hand side.

Once the simulation has been completed, we obtain the following summarized results for the test scenario. The summary of results shows the load increment for each network, the incremental network usage ratio, the financial benefit of services, and the additional costs, as shown in Fig. 16. In this case, we can see that a total 0.1 % increment of network usage for EV-DO and 0.04 % for the HSDPA network. We can also see the expected revenue from newly introduced services (e.g., 222 M$ for EV-DO and 78 M$ for HSDPA). We can analyze the economic effects of the newly introduced services by combining both sides of the cost and benefit. It is very helpful to design new services from a perspective of the market value of service promotion.

The load increment for each network and the network usage ratio increment could be shown for each service in the service combination set. In this service scenario, Service1 and Service2 are newly introduced into the service combination set. The load increment for each network and network usage ratio increment can be estimated at the level of the test region, nationwide, or for a single base station area in the DSS.

Figure 17a shows the effects of new services introduced into each network compared with existing services. In this example, Service1 added 7,664 Mbit of traffic (in the target area known as “milyang”) to the existing EV-DO network, which constituted up to 0.98 % of the existing services, and an increase of 10,575 Mbit traffic to the existing HSDPA network, which constituted up to 1.21 % of the existing services. Service2 caused an increase of 946 Mbit in the EV-DO network, which was 0.12 % greater than the existing services. Figure 17b shows the load increases for each new and existing service, indicating the total load due to each service, particularly new services. Our example shows that Service1 comprised 0.092 % and Service2 comprised 0.011 % of the EV-DO network, while Service1 comprised 0.0425 % of the HSDPA network.

The financial benefit and additional cost of newly introduced services were also estimated for DSS. Based on the defined financial benefit of each service in Table 1 and the target number of service subscribers, we estimates the expected revenue for newly introduced services (the target number of service subscribers was defined by the marketing plan of the service operator). Figure 18 shows the 3-year net present value for the newly introduced Service1 and Service2. Our analysis of the financial benefit based on the network load provides important insights for the design of new services. The efficient usage of network resources is a critical aspect of network



Bad BS Log

Time: BS Type (Sat. Lvl)

181: HSDPA (57,01)
171: HSDPA (23,56)
171: EVDO (85,09)
166: HSDPA (66,25)
161: EVDO (63,95)
156: HSDPA (88,83)
156: HSDPA (73,53)
156: EVDO (82,84)
151: EVDO (80,65)
141: HSDPA (41,07)
141: EVDO (83,27)
31: EVDO (50,38)
16: HSDPA (72,61)
11: HSDPA (83,31)
11: EVDO (87,51)
6: HSDPA (86,64)
6: HSDPA (85,61)
6: EVDO (85,46)

EVDO	100.00
HSDPA	100.00

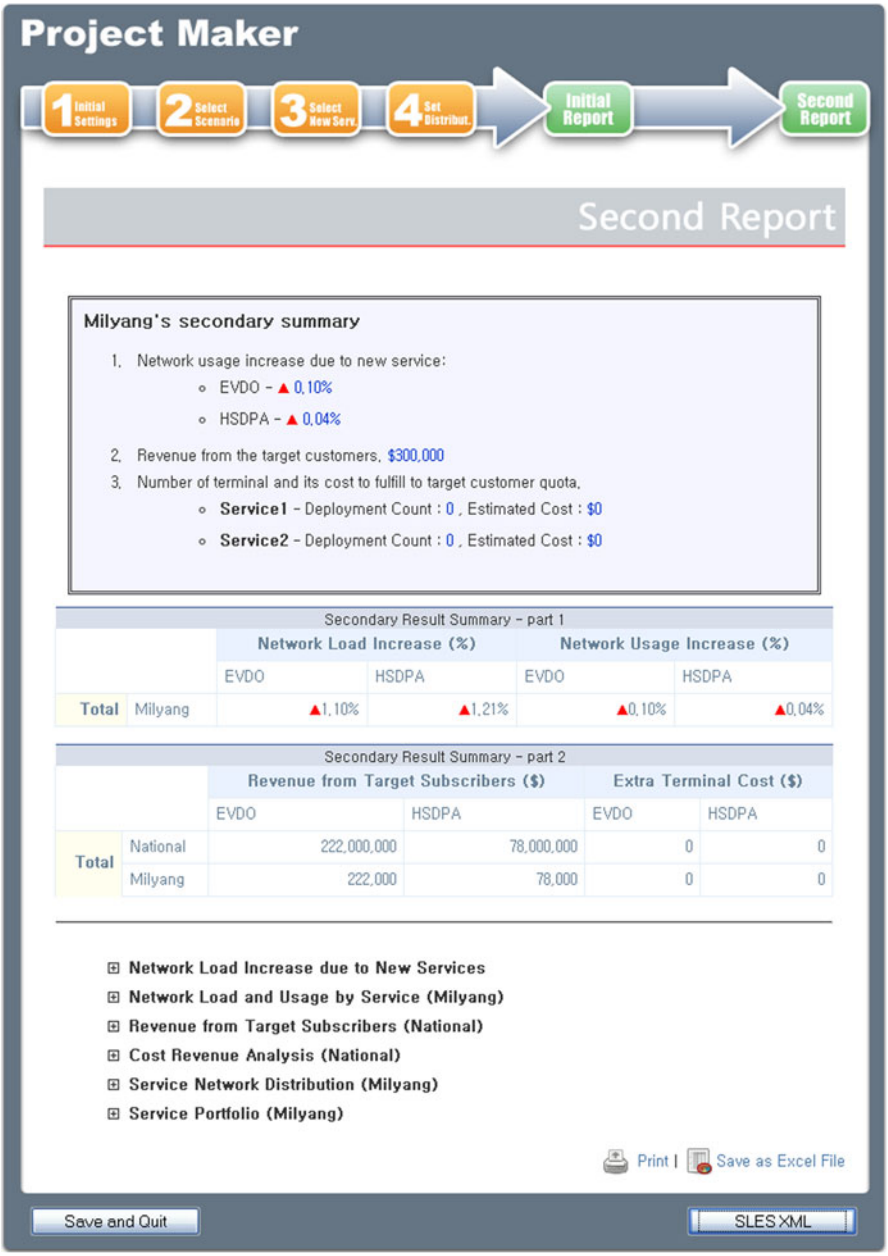
22%

Milyang Scenario

Location	Milyang	Supported Networks	EVDO, HSDPA
Time Frame	Evening	Supported Service	• 1mm • Action Adventure • Action RPG • Additional Movie Service • Arcade See more (91)...
Simluation Duration	1000seconds	Terminal Types	• EVDO High-end • EVDO Low-end • HSDPA High-end • HSDPA Low-end • WCDMA High-end • WCDMA Low-end • WiBro Low-end • EVDO/WCDMA Low-end • HSDPA/WiBro Low-end • EVDO/HSDPA Low-end
Comments		Number of Base Stations	8

Fig. 15 Snapshot of simulation running

management because of the data explosion due to smartphone applications. The network operator should compare the advantages and disadvantages of introducing new services based on resource management and cost control. The DSS results



Second Report

Milyang's secondary summary

1. Network usage increase due to new service:
   - EVDO - ▲ 0.10%
   - HSDPA - ▲ 0.04%
2. Revenue from the target customers. $300,000
3. Number of terminal and its cost to fulfill to target customer quota.
   - **Service1** - Deployment Count : 0 , Estimated Cost : $0
   - **Service2** - Deployment Count : 0 , Estimated Cost : $0

Secondary Result Summary - part 1

		Network Load Increase (%)		Network Usage Increase (%)	
		EVDO	HSDPA	EVDO	HSDPA
Total	Milyang	▲1.10%	▲1.21%	▲0.10%	▲0.04%

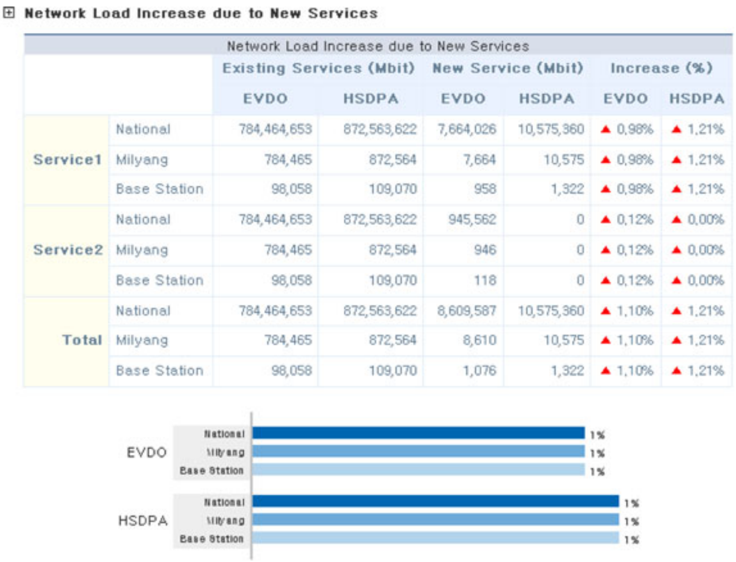
Secondary Result Summary - part 2

		Revenue from Target Subscribers ($)		Extra Terminal Cost ($)	
		EVDO	HSDPA	EVDO	HSDPA
Total	National	222,000,000	78,000,000	0	0
	Milyang	222,000	78,000	0	0

Fig. 16 Summary of results

provide basic information for network resource management and the market promotion of new services.

Finally, we obtain the service portfolio strategy. The service portfolio strategy contains the recommended network and service quality level for each service.

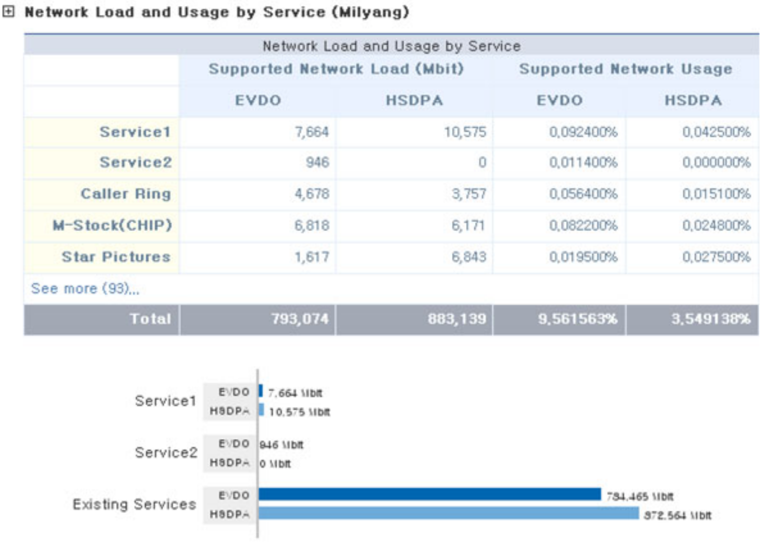


⊞ **Network Load Increase due to New Services**

Network Load Increase due to New Services

		Existing Services (Mbit)		New Service (Mbit)		Increase (%)	
		EVDO	HSDPA	EVDO	HSDPA	EVDO	HSDPA
Service1	National	784,464,653	872,563,622	7,664,026	10,575,360	▲ 0,98%	▲ 1,21%
	Milyang	784,465	872,564	7,664	10,575	▲ 0,98%	▲ 1,21%
	Base Station	98,058	109,070	958	1,322	▲ 0,98%	▲ 1,21%
Service2	National	784,464,653	872,563,622	945,562	0	▲ 0,12%	▲ 0,00%
	Milyang	784,465	872,564	946	0	▲ 0,12%	▲ 0,00%
	Base Station	98,058	109,070	118	0	▲ 0,12%	▲ 0,00%
Total	National	784,464,653	872,563,622	8,609,587	10,575,360	▲ 1,10%	▲ 1,21%
	Milyang	784,465	872,564	8,610	10,575	▲ 1,10%	▲ 1,21%
	Base Station	98,058	109,070	1,076	1,322	▲ 1,10%	▲ 1,21%

(a) Increment of load for each network



⊞ **Network Load and Usage by Service (Milyang)**

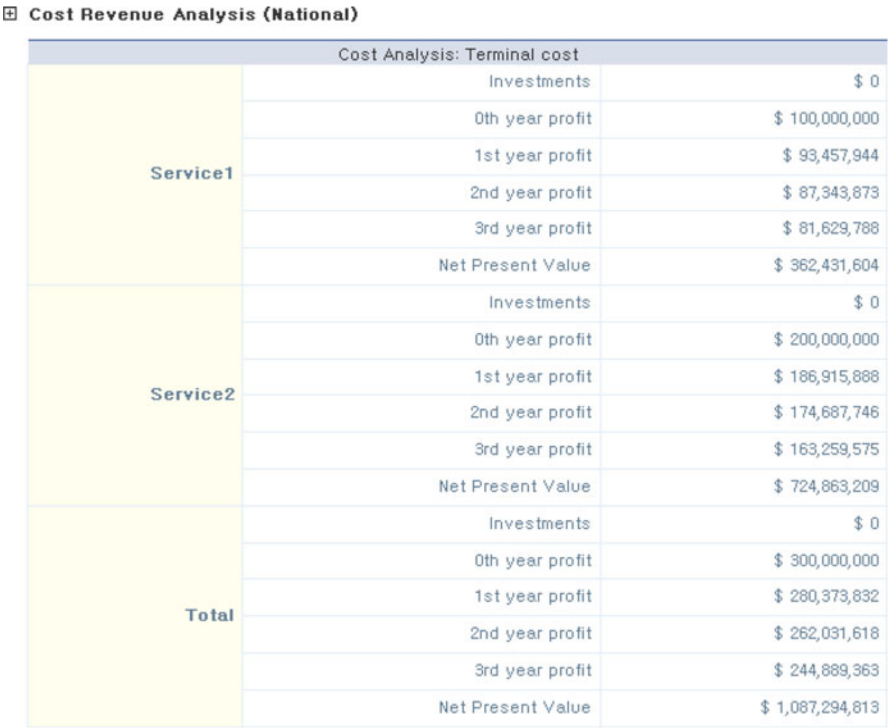
Network Load and Usage by Service

	Supported Network Load (Mbit)		Supported Network Usage	
	EVDO	HSDPA	EVDO	HSDPA
Service1	7,664	10,575	0,092400%	0,042500%
Service2	946	0	0,011400%	0,000000%
Caller Ring	4,678	3,757	0,056400%	0,015100%
M-Stock(CHIP)	6,818	6,171	0,082200%	0,024800%
Star Pictures	1,617	6,843	0,019500%	0,027500%
See more (93)...				
Total	**793,074**	**883,139**	**9,561563%**	**3,549138%**

(b) Increment of network usage ratio

Fig. 17 Network load and usage ratio

Table 3 shows the service portfolio components of the tested service scenario. The service portfolio for each network provides basic guidelines for optimal network operation.



⊞ Cost Revenue Analysis (National)

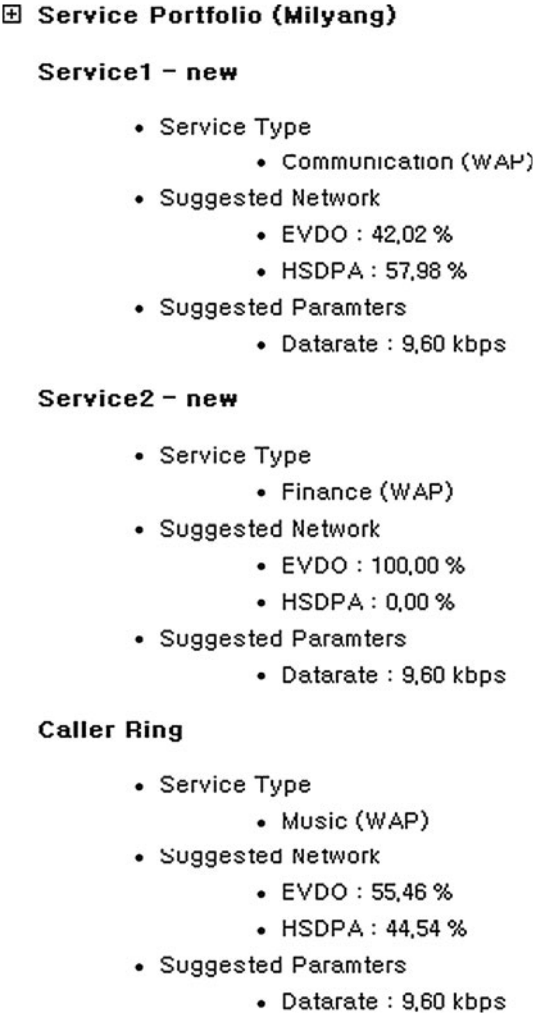
Cost Analysis: Terminal cost		
Service1	Investments	$ 0
	0th year profit	$ 100,000,000
	1st year profit	$ 93,457,944
	2nd year profit	$ 87,343,873
	3rd year profit	$ 81,629,788
	Net Present Value	$ 362,431,604
Service2	Investments	$ 0
	0th year profit	$ 200,000,000
	1st year profit	$ 186,915,888
	2nd year profit	$ 174,687,746
	3rd year profit	$ 163,259,575
	Net Present Value	$ 724,863,209
Total	Investments	$ 0
	0th year profit	$ 300,000,000
	1st year profit	$ 280,373,832
	2nd year profit	$ 262,031,618
	3rd year profit	$ 244,889,363
	Net Present Value	$ 1,087,294,813

Fig. 18 Financial analysis

6 Concluding Remarks

Wireless service operators should build the best service portfolio strategy for each user by focusing on the maximum benefit to network convergence, while maximizing the overall network utilization. The Decision Support System (DSS) is one of the best methods of producing service portfolios for every user in multiple access networks. Service designers, customer relationship managers, and network engineers can build the best match relationship between services and networks and enhance user utilization via our easily accessible web-based DSS for service portfolios. Our objective was to develop a new web-based DSS for a service portfolio strategy in heterogeneous network convergence environments. We adopted an optimal heterogeneous network operation framework, which consisted of multi-stage linear programming and a policy-based market-driven network access method. A market-based marginal cost function was used to evaluate the relative value of resources in each network. These mathematical methodologies were tightly integrated to the decision process of the DSS. Moreover, an integrated two-level simulator provided sufficient justification and enhanced the mathematical approaches. The tightly

Table 3 Exemplar of a service portfolio



⊞ **Service Portfolio (Milyang)**

Service1 – new

- Service Type
    - Communication (WAP)
- Suggested Network
    - EVDO : 42,02 %
    - HSDPA : 57,98 %
- Suggested Paramters
    - Datarate : 9,60 kbps

Service2 – new

- Service Type
    - Finance (WAP)
- Suggested Network
    - EVDO : 100,00 %
    - HSDPA : 0,00 %
- Suggested Paramters
    - Datarate : 9,60 kbps

Caller Ring

- Service Type
    - Music (WAP)
- Suggested Network
    - EVDO : 55,46 %
    - HSDPA : 44,54 %
- Suggested Paramters
    - Datarate : 9,60 kbps

integrated overall decision process is unique in the telecommunications industry. The utility of web-based DSS in an optimal heterogeneous network operation framework provides opportunities for designing new services. The network effect of newly designed services could be tested and adapted to any given network environment by testing the functionality of the DSS. Our practical application of DSS demonstrated the appropriate decision-making process for new service adaptation in a service portfolio. It also demonstrated efficient resource assignment based on multistage linear programming and marginal cost functions in a heterogeneous network environment.

Appendix 1

The minimization problem is stated as follows:

Minimize the total cost $T(u_1, u_2, \ldots, u_N) = \int_0^{u_1} f_1(u)du + \cdots + \int_0^{uN} f_N(u)du$ subject to the constraints $u_1 \geq 0, \ldots, u_N \geq 0$ and $u_1 + u_2 + \cdots + u_N = C$. Because the domain is compact, the total cost function has the minimum in its domain. The Karush–Kuhn–Tucker conditions require that there are constants $\eta_1, \ldots, \eta_N, \lambda$ such that for $k = 1, 2, \ldots, N$,

$$\begin{aligned} \frac{\partial}{\partial u_k} T(u_1^*, \ldots, u_N^*) - \eta_k + \lambda = 0, \\ u_k^* \geq 0, \\ \eta_k \geq 0, \\ \eta_k u_k^* = 0, \end{aligned}$$

and $u_1^* + \cdots + u_N^* = C$. Therefore, if $u_k^* > 0$ for all $k = 1, 2, \ldots, N$, then $f_1(u_1^*) = f_2(u_1^*) = \ldots = f_N(u_N^*)$.

Appendix 2

We will prove that $V(t)$ converges to zero as the time t approaches infinity.

Let $A_{ij} := c_{ij}(f_i(u_i) - f_j(u_j))$. The total traffic $u_1 + u_2 + \cdots + u_N$ is conserved over time because

$$\frac{d(u_1 + u_2 + \cdots + u_N)}{dt} = -\lambda \sum_{i,j} A_{ij} = 0 \quad \because A_{ij} = -A_{ji}$$

Because $A_{ij} = A_{ji}$ and the marginal costs functions are increasing, we have

$$\begin{aligned} \dot{V} = \frac{d}{dt} \sum_{i,j} c_{ij}(f_i(u_i) - f_j(u_j))^2 &= 2 \sum_{i,j} A_{ij}(f_i'(u_i)\dot{u}_i - f_j'(u_j)\dot{u}_j) \\ &= -2\lambda \sum_{i,j} A_{ij} \left(f_i'(u_i) \sum_k A_{ik} - f_j'(u_j) \sum_k A_{jk} \right) \\ &= -2\lambda \left(\sum_{i,j} \sum_k f_i'(u_i) A_{ij} A_{ik} - \sum_{i,j} \sum_k f_j'(u_j) A_{ij} A_{jk} \right) \\ &= -4\lambda \left(\sum_i f_i'(u_i) \sum_{j,k} A_{ij} A_{ik} \right) \\ &= -4\lambda \sum_i f_i'(u_i) \left(\sum_k A_{ik} \right)^2 \\ &= -\frac{4}{\lambda} \sum_i f_i'(u_i)(\dot{u}_i)^2 \leq 0, \end{aligned}$$

which implies that $V(t)$ always decreases unless the traffic distribution $(u_1(t), \ldots, u_N(t))$ is not in a unique equilibrium state. Because $V(t)$ is bounded below, we should have $\dot{V} \to 0$ as $t \to \infty$. However, $\dot{V} = 0$ if and only if $\dot{u}_i = 0$ for all $i = 1, \ldots, N$, which is also equivalent to the equation $f_1(u_1) = f_2(u_2) = \ldots = f_N(u_N)$, leading to $V = 0$. Therefore, as the dynamics evolve over time, it follows that $\dot{u}_i \to 0$ ($i = 1, \ldots, N$). This completes the proof.

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