A Multiscale Real-Time Navigation and Communication Satellite Simulation Model for OMNeT++

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ABSTRACT

This paper presents the first steps of developing the *Galileo Satellite Communication Simulator* (GSCS) based on the INET Framework [2] of OMNeT++ simulation engine [1]. We present our mobility model for the accurate prediction and modeling of satellite motion using NORAD's (North American Aerospace Defense Command) propagation algorithm SGP (Simplified General Perturbations) for real-time satellite position modelling.
Galileo specific satellite orbit data is generated in order to establish the mobility of the prospective space segment. The validity of the simulation implementation is then proved by comparing the results of our simulation with two reputable satellite tracking applications and to a real GPS receiver, from which further extensions of the simulation system are derived. In further steps the integration in a *Multiscale Network Simulation Environment* is described. The dynamic interaction between Environment, Radio Channel and User Mobility can then be modelled in an adequate way.

Categories and Subject Descriptors

I.6.4 [**Simulation and Modelling**]: Model Validation and Analysis; I.6.5 [**Simulation and Modelling**]: Model Development; I.6.6 [**Simulation and Modelling**]: Simulation Output Analysis

General Terms

Performance, Design, Reliability, Experimentation, Verification

Keywords

Galileo, Multiscale Simulation Environment, Satellite Mobility Model, SGP4/SDP4, Two Line Elements

1. INTRODUCTION

The European satellite navigation system *Galileo* offers a promising technology to enhance the navigation resolution and offers communication capabilities in combination with the actual *Search and Rescue* (SAR) service of the COSPAS-SARSAT system. Our actual research focus in the project *Galileo4FireBrigades* lies on real time emergency communication services for firefighters even if no terrestrial network is available. We are developing a hybrid communication architecture with the objective to support out-of-coverage communication using the enhanced SAR Service.
The Galileo System will be ready for use by 2013 and our objective is to prove the real time capability of the SAR Service with the proposed *Galileo Satellite Communication Simulator* (GSCS) framework.
This paper presents the results of the first stage of development of GSCS, which is the accurate modeling of the satellites' motion and position based on NORAD's propagation algorithm SGP (Simplified General Perturbations) and the further developments SDP (Simplified Deep Space Perturbations) for real-time satellite position prediction.
In order to enhance the simulation model itself, a *Multiscale Simulation Environment* (MNSE) is built up which relies on a tight coupling of an industry standard Radiowave Propagation Simulator (RPS) and a CNI proprietary MObile Object Simulation Environment (MOOSE) to OMNeT++. In order to create a holistic system model of a wireless communication network, a Central Event Broker (CEB) is set up in a form of a OMNeT++ simulation module. The CEB manages the synchronization and the distribution of events which transit from one simulator to another. To indicate the feasibility, a multiscale sample of this satellite communication system, comprising three mono scales, namely protocol, radio propagation and user mobility, is used here. Opposed to state-of-the-art multi-layer simulation systems [13], the MNSE is not focused on the optimal interworking between entities but rather supports their individual degree of freedom in order to engulf a vast problem space.
This paper is arranged by presenting a brief introduction to the SGP4 and SDP4 algorithms in addition to an explanation of NORAD's Object Catalog in the second section. Key aspects of the implementation of our simulation model in OMNeT++ are discussed and two visualisation approaches namely Global Projection View (GPV) and Local Projection View (LPV) are described. Finally the validity of the accuracy and reliability of the simulation model is proven

against well-known satellite tracking applications and a real time GPS track followed by the generation of Galileo satellite movements. Special implementation aspects on the simulative Galileo Satellite models and Ground Stations are described in detail in section 3. In section 4 the multiscale simulation approach is depicted before the approach is turned in to a formal architecture. We provide insight to the technology used for coupling the distinct simulation engines. A representative simulation flow is described, too, before this paper is wrapped up by an *Galileo4FireBrigades* application example.

2. THE SATELLITE MOBILITY MODEL

2.1 Introduction

NORAD was founded by USA and Canada for space observation as a reaction to USSR's launching the first satellite in 1957. The primary task of NORAD was to provide defence against intercontinental ballistic missiles. In order to differentiate between missiles and satellites, all moving objects in the earth's orbit are tracked continuously by a large network of sensor base stations and the measurements are archived as Two Line Elements (TLE) in NORAD's Object Catalog. Since the sensor base stations are not able to track the satellites continuously, an algorithm called Simplified General Perturbations (SGP) [4] was developed to forecast the movement.

We propose using this algorithm in order to generate a highly precise real time satellite mobility model for OMNeT++. In combination with the actual NORAD Object Catalog, all kinds of moving objects in the earth orbit can be tracked. Even the motion and position of International Space Station (ISS) and the Space Shuttle can be displayed by using relevant TLEs. A simplified satellite mobility model could

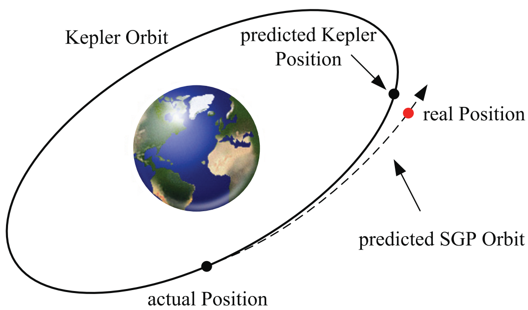

Figure 1: SGP Prediction

be realised by modeling the movement based on regular Kepler traces, but due to the absence of irregular perturbations in Kepler traces that actually arise during a satellite's motion, the trace of the satellite can not be modeled accurately then. Figure 1 illustrates the difference between the two approaches.

2.2 The Propagation Algorithms

2.2.1 *Simplified General Perturbations No.4*

The Simplified General Perturbations No.4 (SGP4) [5] algorithm is an extension of the originally developed SGP prediction algorithm. The calculation is accomplished by adding the following effects to the regular Kepler Traces:

- Secular effects of atmospheric drag and gravitation pull are calculated and added to the initial anomaly.
- Long periodic and short periodic changes are added.
- Zonal harmonic terms of the earth's gravitation field are calculated.

This algorithm is suitable for near earth orbits which usually takes less than 225 minutes to complete one revolution around the earth.

2.2.2 *Simplified Deep Space Perturbations No.4*

The Simplified Deep Space Perturbations No.4 (SDP4) [5] algorithm can be used for deep space satellites, which have a revolution time of more than 225 minutes. The calculation is based on the SGP4 algorithm, introduced previously, and accomplishes additional calculations taking into account the following:

- Influence of lunar and solar gravity fields
- Certain earth harmonics, which are important for half-day to full-day periods.

The proposed implementation [8] selects the suitable algorithm automatically. This API is integrated into the INET Framework in order to minimize errors caused by a self implementation.

2.3 Two Line Elements

The actual TLE sets can be downloaded at [6] and [7] either as a full object catalog or a system specific set. Several other information relating satellite tracking can also be found on these websites. The parameters of the TLE for-

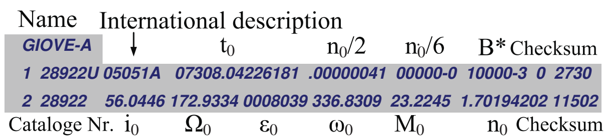

Figure 2: Two Line Element Format

mat used by the SGP4/SDP4 algorithms are shown in Figure 2 whereas Table 1 describes the various abbreviations of the TLE format. Each TLE data set consists of three lines

Parameter	Description
t_0	Epoch Time
n_0	Mean Motion
B^*	Resistance Parameter
i_0	Inclination
Ω_0	Right Ascension
ϵ_0	Eccentricity
ω_0	Argument of Perigee
M_0	Mean Anomaly

Table 1: TLE Description

whereas line 0 consists of a 24 character name and line 1 and 2 contain the described data to accomplish the calculation.

2.4 Implementation in OMNeT++

This section discusses the key features and visualisation approaches of our simulation implementation developed using the INET Framework of OMNeT++ version 3.3 simulation software engine.

2.4.1 *Two Line Element Update*

In order to retain the accuracy of the mobility model, reasonable TLE data updates are necessary because of unpredictable changes in the orbit. These changes are observed by the ground stations and inserted in new TLE data. New TLEs are available every 6 to 10 hours for Low Earth Orbit (LEO) satellites and approximately once a week for geostationary satellites. Hence the needed TLE update for real time prediction depends on the kind of modeled satellites. The implementation offers a parser functionality, which provides an easy way to update TLEs by just copying the downloaded text files to the simulation directory. Only satellite names and the file name have to be assigned in the simulation initialization file. In order to minimize the parser process, TLE data files should be limited to the specific satellite system.

2.4.2 *Real Time Synchronization*

The actual system time of the local computer is taken for the reference time and used for the start point of the movement prediction. For this reason TLEs have to be updated reasonably. The user specific time zone has to be assigned in the OMNeT++ initialization file since the TLE epoch time bases on Greenwich Mean Time (GMT) at 0°longitude.

2.4.3 *Global Projection View (GPV)*

In this visual projection, the satellite mobility is presented via a 2-dimensional global view (Figure 3). This 2-D view of the globe is made by transforming a relevant World Map, which can be downloaded from [9] for non-profit use, using the *Cylindrical Equidistant Transformation*, since this approach is the natural projection because the *x–coordinate* is equal to geographic length and *y–coordinate* is equal to geographic width. The calculated satellite positions are represented in longitude, latitude and elevation notation and in order to plot the position of the satellites accurately over our 2-D map the following equations are used:

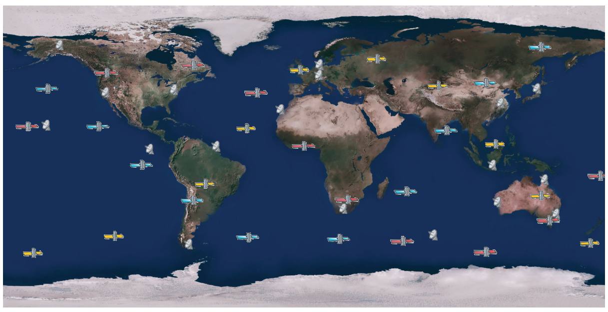

Figure 3: OMNeT++ GSCS Simulation View: Galileo satellite system in Global Projection

$$pos.x = (((\frac{map.x}{360} * longitude) + (\frac{map.x}{2})) \mod (map.x))$$

$$pos.y = (-(\frac{map.y}{180}) * latitude + (\frac{map.y}{2}) \mod (map.y))$$

where $map.x/y$ are the dimensions of the chosen map. The modulo operation is necessary to let the satellite appear on the other side of the map before leaving the simulation playground. The resulting GPV as viewed in the OMNeT++ environment is presented in Figure 3. This visualization can be used for presentations and analysis of a holistic satellite system.

2.4.4 *Local Projection View (LPV)*

This visualization depends on the actual position of the user equipment in order to evaluate the performance of a satellite system at a specific time and position. The exact user position can be assigned in the initialization file of the simulation. Visible satellites are located in the inner circle and have an elevation higher than 10°as shown in Figure 4. Non visible satellites are at the gray border of the outer circle. The calculation depends on azimuth and elevation degree calculated by the prediction algorithm. These values are converted in the shown coordinate system (Figure 4) by using the following equations.

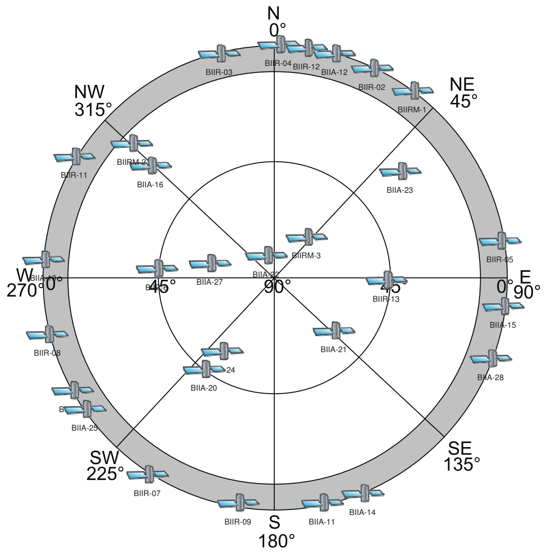

Figure 4: OMNeT++ GSCS Simulation View: GPS system in Local Projection

$$radius = radius_{max} - (\frac{elevation}{\frac{\pi}{2}} * radius_{max})$$

$$pos.x = -cos(Azimuth + \frac{\pi}{2}) * radius + radius_{max}$$

$$pos.x = -sin(Azimuth + \frac{\pi}{2}) * radius + radius_{max}$$

All satellites with an elevation greater than 10°can be assumed as visible as this first assumption relies on a flat scenario with line of sight conditions to the satellite.

2.5 Validation of the Implementation

The reliability and accuracy of our simulation implementation is validated in two steps. In the first step our model is compared to the output of other reputable satellite tracking applications. In the second step we validated the simulation output against the real GPS System in order to evaluate the constraints of assumptions made.

2.5.1 *Comparison to reputable satellite tracking applications*

The performance of our simulation model is compared against HeavenSat [10] and WxTrack [9], which are two popular satellite tracking applications. Both programs are using the described SGP algorithm and Two Line Elements to predict satellite positions. The TLEs have been updated in all programs short before the measurement began.

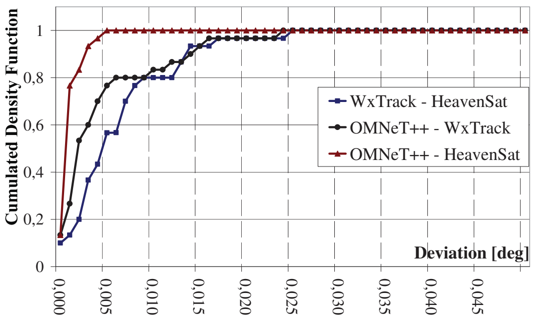

Figure 5: Accuracy in comparison to approved satellite tracking applications

Figure 5 shows the deviation of the azimuth in comparison to the two satellite tracking tools. Only the azimuth degree has been examined, since the other values give analog results. The results show a maximum deviation of 0.025°, which shows, that the implemented algorithm is working correctly. In further steps the calculated satellite positions are assumed to correspond to the real positions.

2.5.2 *Comparison to a live GPS-Track*

In order to prove the 10°visibility assumption, the OMNeT++ implementation is validated by comparing the simulated satellite positions with a live GPS track using *Visual GPS* [11] on a notebook connected with a SIRF Star III GPS receiver. The measurements have shown irregularities which correlate to the composition of the environment. The specific results are not shown here, but lead to a further extension of the simulation by adding a sophisticated environment and channel model.

3. THE GALILEO SYSTEM

3.1 Galileo Space Segment

The prospective European satellite system Galileo is our current research focus. Two Line Element (TLE) data is not available for future satellite launches, hence we created new TLEs using the *Galileo System Simulation Facility* (GSSF) [12] to obtain the orbit data. An existing TLE of the first Galileo satellite GIOVE-A (Galileo in Orbit Validation) was the reference for 30 Galileo operational satellites, which are moving on three different orbits in the Walker 27/3/1 constellation in a height of 23260 km. Three satellites in every orbit are used for quick recovery in case of failure.

Table 2 shows the relevant parameters, which have been transferred to the TLE Format. The number of satellites which are going to be equipped with Search-and-Rescue modules to enhance the SAR Service integrity are not defined yet.

Parameter	Description
Semir-major axis [km]	29600.318
ϵ_0	0.000
i_0 [deg]	56.00
Ω_0 [deg]	0/120/240
ω_0 [deg]	0
M_0	40 deg dif. between satellites

Table 2: Galileo Orbit Parameters

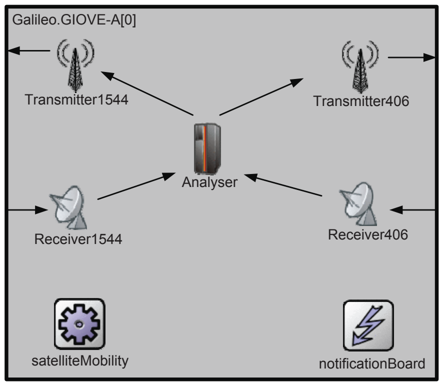

Figure 6: OMNeT++ model of a Galileo satellite

Figure 6 explains the OMNeT++ simulation model of the satellite. Two receivers are necessary since one is needed for the *Galileo Control Center* Up– and Downlink on a frequency of 1544MHz and the second is for the SAR module operating on a frequency of 406MHz. A short time delay before the signal reaches the *Analyser* to be processed is implemented. The *Analyser* is able to handle one emergency call at a time. If no GPS/Galileo position is transmitted with the emergency call, the *Analyser* starts the localization process using the Doppler Effect. This localization approach can only be accomplished by Low Earth Orbit (LEO) or Medium Earth Orbit (MEO) satellites because of the relative movement to earth. Another delay is implemented to consider the delay for sending the information down to the sensor stations using *Transmitter1544*. The second *Transmitter406* is used for the Galileo specific acknowledgement to inform the emergency caller for receiving the message. These simplified assumptions meet our requirements in order to validate the propagation and processing delay for the SAR Service.

3.2 Galileo Ground Segment

The future Galileo ground segment consists of 29 sensor stations for tracking relevant signals from the orbits. Additionally 5 uplink stations are responsible for movement correction and controlling processes. Figure 7 describes the model of a Galileo sensor station in detail. *Receiver1544* receives the emergency call containing position information of the caller. The *Analyser* checks the signal and sends it out to the *Search–and–Rescue Center* of the COSPAS-SARSAT system on a terrestrial way using a fiber optic connection.
The largest segment which has to be taken into account is the *user segment*. A wide spread of new navigation and communication applications is expected within the next few years. We integrate this user group in the Multiscale Network Simulation Environment (Section 4) and add a LPV

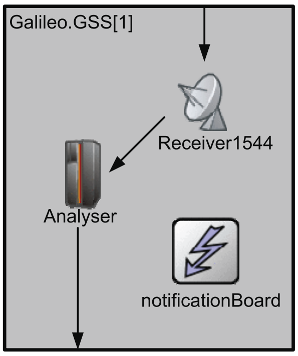

Figure 7: OMNeT++ model of a Galileo Sensor Station

for embedding the satellite system to the local scenario. The resulting Galileo System in a simulation view is shown in Figure 3. The divers satellite color indicate the movement on different orbits.

4. MULTISCALE SIMULATION

In order to generate a holistic model of a *Wireless Communication Network* (WCN), the dynamic mutual impact of environment, network infrastructure and mobile objects must be included in the model. Especially wireless ad–hoc networks provide connections which are vulnerable to effects like multipath fading, dispersion and *non–line–of–sight* (NLOS) conditions. In this context, mobile objects are not necessarily subscribers of the network as even a moving passive *object* may cause variations in the radio channel and in turn may influence network performance. Currently, OMNeT++ does not model these dynamic interactions precisely but rather focuses on protocol aspects of mobility as such. Radio propagation models are therefore kept straightforward and rather static. Implemented user mobility models are supported on a very basic level only. It is, of course, beyond the current scope of the INET– or Mobility–Framework [3], to model all the occurring dynamic dependencies which have essential effects in a holistic wireless network model. To gain capabilities for a modelling precision which is adequate to evaluate even safety critical systems, significant extensions to the INET simulation framework are presented in this paper. Several claims are made by this modelling approach:

- A 3-D environment editor captures **reasonable application scenarios**. The scenario model generated by either *Google SketchUp* or the Radiowave Propagation Simulator (RPS) front end [14] lays out the foundation of each model.
- **Realistic modelling of user mobility** is enabled by addressing *dedicated path mobility* and *dynamic group mobility*. These features are supported by the Mobility Simulator MOOSE [15].
- An **industry standard channel model** at high accuracy is derived from the results of the RPS simulation due to the ray tracing features of that component.
- The **full model dynamics** is captured by the *Central Event Broker* (CEB) which manages the synchronized, mutual exchange of status data between all simulation components.

4.1 Multiscale Simulation Model

The central paradigm of the *Multiscale Simulation Architecture* (MSA) is the classification of **source models** and a (holistic) **system model** [16] which interact by means of a central **event broker**. A **source model** is thought to represent network participants (both active and passive), the so called *objects* in the model context. It comprises all aspects of activity for each object. This addresses network traffic models as well as movement and physical parameters or capabilities. Especially radio parameters such as transmit power, antenna configuration or receiver sensitivity are valid examples for the latter. In general, a source model is located in the genuine OMNeT++ domain and thus utilizes all the features of the standard INET framework.

A **system model** represents twofold dynamic interactions of all the source model entities. First, physical models like radio propagation, individual antenna models and entity location determine the physical connectivity. In turn results of such a model may have impact on activity models in some of the source entities. Similar, individual movement may cause group effects which are handled by the specific mobility simulator in the system model. The utilization of best–in–class tools for these complex sub systems advocates the open system solution presented later on.

The **CEB** ensures time synchronisation between source and system models, and therefore between all simulators. It does so by routing relevant data to the affected entities. An integrated decision support function schedules only relevant update processes in order to minimize the calculation overhead.

Figure 8 depicts the described MNSE along with the most relevant information flows as an extension to the OMNeT++ simulation framework. The *Central Event Broker* (CEB), operating as an adjunct to the well known *ChannelControl* module, defines the core of the MNSE. The topology setup for the next simulation interval is determined by those core components.

4.2 Simulation Architecture

4.2.1 Components and Interaction relations

To turn the basic concept as described in section 4.1 to a valid executable, the concept components have been embedded into a specific framework as shown in figure 9. The CEB defines the context, in which the OMNeT++ simulation is run and all subsidiary simulators (RPS, MOOSE and genuine OMNeT++) are executed. The CEB mediates the data flow between the coupled simulators and also makes use of several supplementary tools which are grouped around the core. The *User Interaction* component is responsible for the GUI driven capturing of the application scenarios. The RPS front end has been chosen to be used for this task, applying the spatial model to all other simulators as input.

The control of the simulation flow and an online result processing has been implemented as a separate GUI while the central data management is set up as a link to a MySQL data base.

As far as communication links are not predefined for the exchange of status data, the CEB utilizes TCP sockets to transfer all necessary information between different entities.

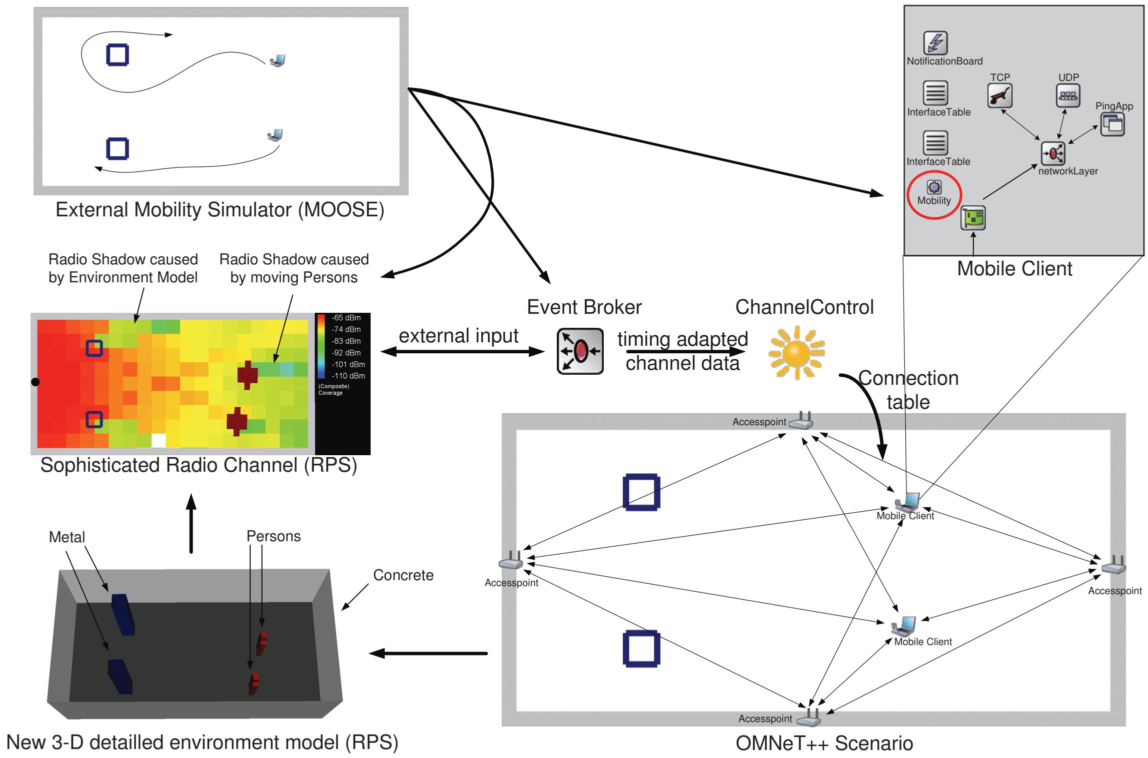

Figure 8: Multiscale Network Simulation Environment

Solid arrows indicate dynamic exchange of information as long as the simulation is active. Dashed lines represent information which is generated in a pre-run. As for now, a dynamic *change of plan* with respect to the movement pattern is not implemented in the network objects.

4.2.2 Coupling the Simulation Environments

As not all considered models might require online data exchange, two different types of simulator interfaces are used, namely a **passive** one (dashed lines in figure 9) and an **active** one (solid lines in figure 9).

The passive interface

The passive interface is considered to be a storage and retrieval process from a central database only. A generating simulator (here MOOSE) will generate all information in a pre–run and store the results in the data base from which the CEB will retrieve a snapshot of all positions any time this is needed. This has been implemented by means of an MySQL data base to achieve a high degree of flexibility.

The active interface

The active interface is a superset of the passive one in the sense that the data source may update the information in the data base while the simulation is executing. As an example, coverage of a particular location in a WCN may change due to fading effects if objects move. If the valid scope of information is just bilateral and temporal, a simple TCP socket connection is established between source and sink by the CEB. Furthermore, socket connections are used by the CEB to trigger update runs of the system model.

4.3 Simulation flow

Actual CNI research activities on indoor localization with IEEE 802.15.4/ZigBee [18] networks and Mobile WiMAX rely on the presented MNSE. In these settings, a passive interface has been chosen for the mobility model as no strategy simulation for user behaviour as a function of communication performance is considered. Movements may therefore be as well preassigned. However, as the nodes in the examples perform power control at the transmitter, a preassignment of radio connectivity is prohibited as power conservation strategies are one of the facets of the research projects mentioned.

As external simulators are executed in parallel to OMNeT++, we have activated multi threading in the code. As an example, each entity may request an update of the radio channel parameters from the event broker for a target time t. The CEB triggers the appropriate simulator to deliver the result in a new *service thread* and inserts a new *service event* into the queue of the OMNeT++ main thread. That event will block the simulation when scheduled if the service thread did not terminate in time. If the servicing simulation returns a result, the associated CEB service thread will store it in the central data base and terminate afterwards. The *service event* causes a reload of the model setup after unblocking and thus leaves the overall simulation in the correct, new state.

4.4 Propagation Example

The accuracy of the MNSE channel model is detailed using a simple Wireless LAN example as shown in Figure 10. An isotropic WiFi source is sending at a power of 100mW. Three 50cm concrete walls are modelled to describe the en-

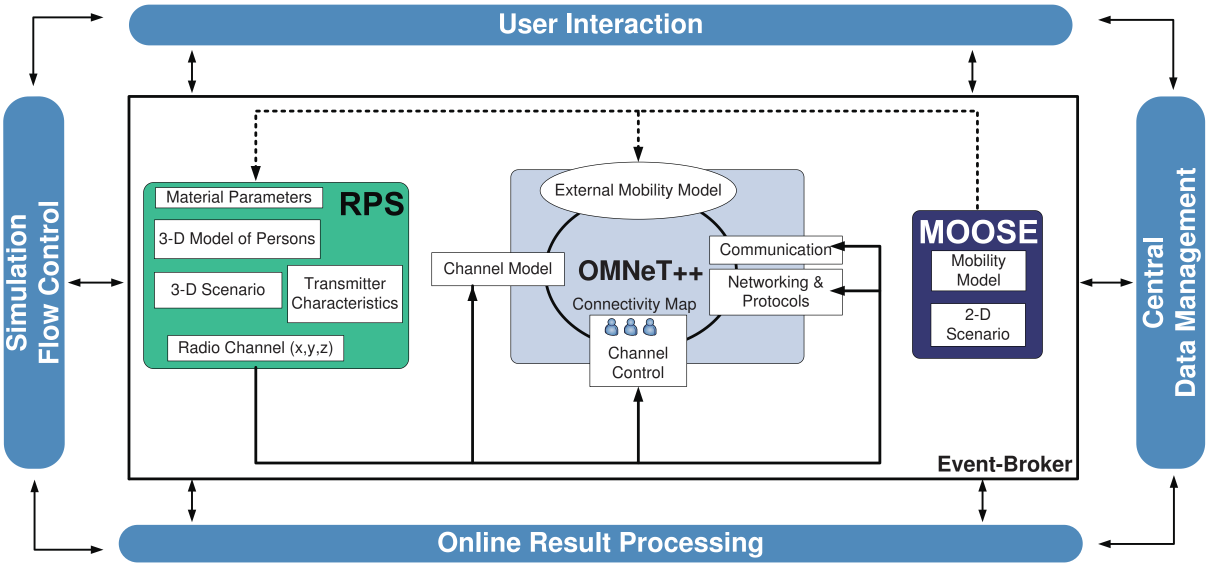

Figure 9: Implementation of the multiscale simulation model

vironment. The receiver is positioned behind the wall and for this reason invisible for the transmitter. The indicated direct path (Figure 10) between transmitter and receiver is examined. At first the received power is calculated using the theoretical *static path loss* formula without attending the environment. In the next step a path analysis is executed in RPS. The results illustrated in Figure 11 present the difference between these two approaches.

The radio coverage propagation shown in Figure 10 visu-

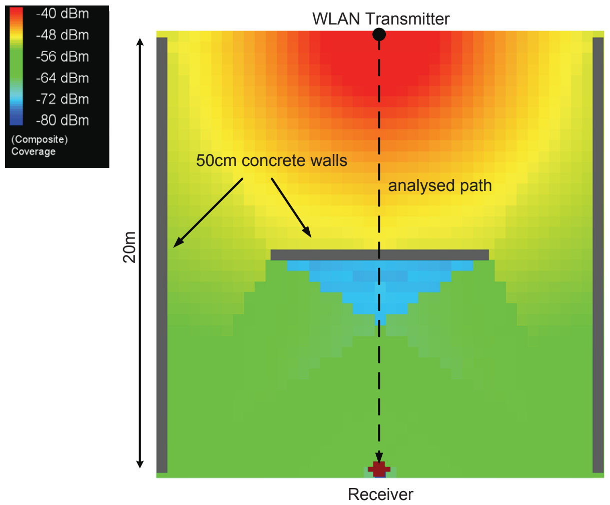

Figure 10: Wireless LAN Radio Channel Example

alizes the characteristics of the RPS graph shown in Figure 11. The first incursion is caused by the concrete wall in the middle of the scenario. The receiving power is then rising rapidly to a constant level because reflections on the outer walls boost the signal. Another incursion is caused by the user themselves. These artefacts are not taken into account by the static pathloss model.

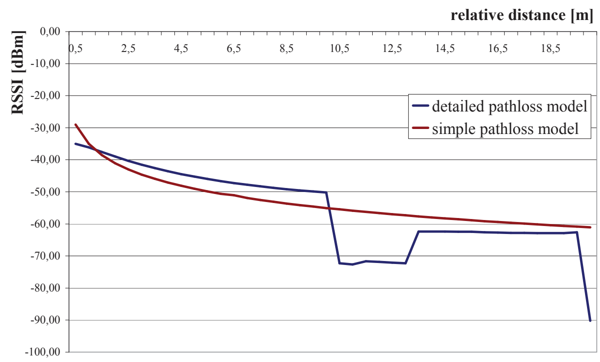

Figure 11: Comparison of simulated and theoretical pathloss model

5. APPLICATION SCENARIO

The *Galileo4FireBrigades* project is focussed on wide area fire fighter missions including *floodwater* and *forest fire* catastrophes. A precise satellite coverage estimation as shown in Figure 12 is needed in the simulation model to make a realistic prediction of the availability of satellite services.

The example scenario was modelled using the RPS front end. A suburban area flooded with water is pictured for this simulation. The GIOVE-A satellite configurations containing transmit power, frequency band and position have been transferred to the RPS ray tracing engine and can be accessed in the OMNeT++ protocol simulation. The satellite's position is about 2500km in eastern direction depending on the local coordinates of the example scenario. We are using the SAR frequency at 406MHz for this coverage prediction.

The free space coverage is uniformly distributed, but especially the coverage around houses shows irregularities caused by reflections on the outer walls. The blue shadows in Figure 12 indicate a very low signal level, as the white shadows indicate that no satellite signal is available.

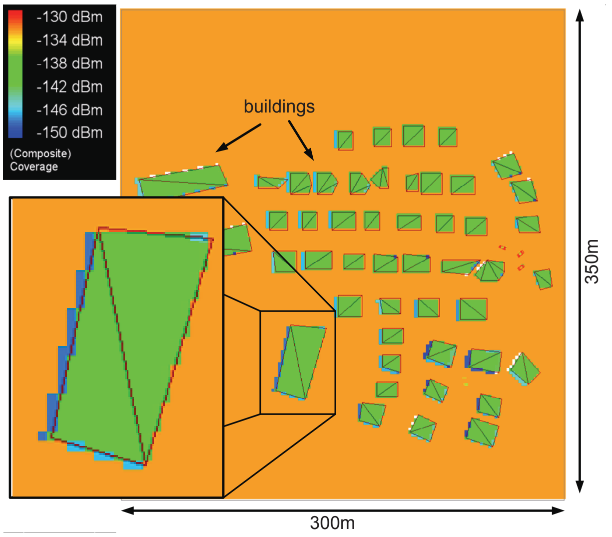

Figure 12: Galileo Satellite GIOVE-A coverage estimation on a local flood water scenario

We propose using the satellite based SAR service only in situations where the user is out of reach from the local communications networks. Hence combining sophisticated user mobility models and a highly precise channel propagation engine, the number and the positions in the local scenario can be estimated where satellite based SAR services are needed. In order to generate a holistic system model, local networks can be included in this scenario additionally to the satellite coverage prediction.

6. CONCLUSION AND FURTHER WORK

As a token of our commitment to the OMNeT++ community, we will be releasing a **Galileo Ready** compilation of the INET Framework. The implementation offers a simple application for satellite tracking without the need of exact knowledge about space architecture and equations. Every satellite currently in the earth orbit and even prospective Galileo satellites can be modelled using this implementation approach. The tracking is highly precise, as proved in section 2, in comparison to reputable satellite tracking applications. Further extensions are including this Galileo system model in the proposed CNI Multiscale Simulation Environment which is coupled to a sophisticated radio channel and a 3-dimensional environment model in order to enhance the simulation model of this wireless satellite communication system. We have shown a *Galileo4FireBrigades* specific application scenario from which the usability in terms of real–time–capability and service availability for fire fighters will be evaluated. We are now able to evaluate the *Galileo4FireBrigades* specific hybrid communication architecture containing terrestrial and satellite communication components.

7. ACKNOWLEDGMENT

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Project: Galileo4FireBrigades – Employment of Galileo services for wide area fire fighter missions – 50NA0724

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