A Tutorial on Trace-based Simulations of Mobile Ad-hoc Networks on the Example of Aeronautical Communications

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Abstract

The OMNeT++ simulator is well-suited for the simulation of randomized user behavior in communication networks. However, there are scenarios, where such a random model is unsuited to evaluate a communication system, and this paper attempts to highlight such a case. Using this example of ad-hoc communication between aircraft mid-flight, a tutorial-style description is attempted that shall show how the OMNeT++ simulator can be used when a wealth of real-world trace data is available. In particular, it is described how mobility trace files can be directly used within OMNeT++, and how to link the generation of data messages to this mobility data. This is explained via an example simulation that evaluates a communication network in which an aircraft notifies the ground control when it enters or leaves a specific geographic region. Additionally, a novel trace-based application has been developed to achieve this link between mobility and message generation. Furthermore, a new TDMA-based medium access protocol for decentralized communication networks is presented, which is oracle-based and thus allows a TDMA-like behavior of medium access without causing any overhead; it can be useful when upper-layer protocols should be evaluated under the assumption of TDMA-like behavior, but isolated from the effects of a full-fledged TDMA protocol. Finally, physical layer behavior is often either overly simplistic or overly computationally expensive. For the latter case, when a detailed channel model is available but its evaluation requires prohibitive computational effort, then averaging its behavior into trace data can find a middle ground between efficient evaluation and realistic representation. Hence, a novel trace-based radio model has been developed that makes use of an SNR to PER mapping. In the spirit of open science, all implementations have been made available under open licenses – please see the conclusion.

1 Introduction

Most of the time, when communication systems should be evaluated through simulation concerning some Key Performance Indicator (KPI), randomized behavior is modeled. This randomization should be bounded to realistic limits so that average cases are simulated most of the time, and edge cases are investigated sometimes. When such a simulation model has been set up, it can be run many times to obtain statistically meaningful results. For example, when the performance of an IEEE 802.11 WiFi protocol should be studied, then it may be sufficient to model web browsing behavior through statistical means such as a negative exponentially distributed “reading time” that passes before the next request is triggered by a user.

Sometimes, however, specialized communication systems are tailored to specific applications and requirements, where randomized behavior does not reflect a realistic utilization of the system. The authors of this paper are involved in a German national research project, where the upcoming *L*-band Digital Aeronautical Communications System (LDACS) is extended by Air-to-Air (A2A) functionality; the Air-to-Ground (A2G) component of LDACS is being standardized by Single European Sky ATM Research (SESAR) and International Civil Aviation

Organization (ICAO) at the time of writing. The details of LDACS are out of the scope of this contribution, but the interested reader may refer to [1], [2] for an introduction. In this particular case, A2A communication involves Air Traffic Control (ATC) and safety-related communication. With this focus, the requirements concerning latency and reliability are fixed, and message generation is clearly defined. For example, when an aircraft enters or leaves an Oceanic Control Area (OCA), it may be required to communicate this event to the authorities. Other examples include requesting to change altitude, or requesting permission to land. These events are thus *bound* to mobility, which in turn is tightly controlled. Moreover, the busiest oceanic airspace – i.e., the most interesting geographic area for LDACS A2A – is the North Atlantic Corridor (NAC), as discussed in [3], [4]. Here, flight routes are pre-assigned by the authorities to follow tracks, which are updated daily to accommodate up-to-date weather conditions and wind streams. In consequence, there exist vast amounts of mobility data of actual flight path traces, and communication data message generation can be directly linked to each aircraft and its mobility.

With such a special-purpose communication system and such pre-determined mobility and data traffic in mind, randomized user behavior is not the right model to evaluate this system's KPIs. Instead, the need arises to use existing mobility and data traffic traces, so that real-world scenarios can be evaluated. In this paper, we aim to show how the OMNeT++ simulator can be used to effectively make use of trace data, so that future research with these specific requirements may benefit. In particular, Sec. 2.2 shows how data traffic generation can be linked to mobility, in Sec. 2.3 how an idealized Time-Division Multiple Access (TDMA) Medium Access Control (MAC) can be implemented, and how a custom radio model can reflect Signal-to-Noise Ratio (SNR) behavior based on data that has a priori been generated using a sophisticated channel model for the respective communication system. Sec. 3 provides the evaluation of an example scenario, where all system model components are present, as aircraft must communicate entering and leaving a particular OCA to a ground station so that messages are linked to user mobility. Finally, Sec. 4 provides a discussion and a conclusion.

2 System Model

This section is concerned with a description of the system model as well as details on the implementations that realize the respective components.

2.1 Trace-based Mobility

Trace-based mobility is, for our needs, sufficiently implemented in OMNeT++ through `BonnMotionMobility`. Aircraft mobility traces are converted to this format, which specifies in each line the coordinates (x, y, z) of a specific aircraft for each moment in time t.

2.2 Trace-based Data Traffic

As motivated earlier, data traffic generation is linked to mobility. For aircraft, certain conditions may trigger the generation of a message, such as entering an OCA, a different flight phase, etc. To achieve this, a novel `UdpTraceBasedApp` inherits from `UdpBasicApp`, which requires an additional `traceFile` configuration parameter. The original `UdpBasicApp`'s `startTime`, `stopTime` and `sendInterval` parameters are ignored. Instead, it expects a `.csv`-formatted text file that contains a simulation time stamp in each line. These time stamps should be monotonically increasing and specify the moment in time where a new message is generated. The interval inbetween messages is therefore provided through this trace file, which should be generated jointly with the mobility trace files to link mobility to message generation. This design allows the greatest flexibility, as different applications – e.g., reporting to have entered or left an OCA as opposed to requesting permission to land – may have different destinations or message sizes. Therefore, each application would be realized through their own `UdpTraceBasedApp` and corresponding trace files.

2.3 Idealized TDMA Medium Access

The design of LDACS A2A presents several challenges. Firstly, the large communication ranges in the order of hundreds of kilometers prevent Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)-like MAC protocols, as radio wave propagation delays exceed 1 ms, so that sensing results are outdated at the time of transmission. The actual MAC protocol for LDACS A2A is therefore a TDMA-based protocol – just as LDACS A2G [5], [6]. Its intricacies will be published at another time, while some particular challenges have already been addressed [7], [8].

Secondly, routing plays a major role in LDACS A2A, as aircraft en route over the NAC will communicate with ground stations outside of their communication ranges i.e., messages must be forwarded by intermediate aircraft until the ground network can be reached. To evaluate routing protocols before the proposed MAC protocol was sufficiently specified and implemented, and to focus on the effects of routing protocols in isolation – without superimposed effects of an underlying MAC protocol – an *idealized* TDMA protocol was required. In a sense, it can be seen as a baseline MAC protocol implementation for time-slotted communication. LDACS A2A provides self-organized communication to users of a Mobile Ad-hoc Network (MANET) with no central coordinator, which means that an allocation of time slots to users is a non-trivial task. The idealized TDMA implementation, on the other hand, allocates time slots to users unrealistically through an oracle: whenever a user requires a transmission slot, it is assigned an exclusive slot without any control overhead. When the focus of evaluation is not the MAC protocol, then this idealized TDMA MAC can be used to automatically assign time slots to users and thus achieve the characteristics of a TDMA system. In some MANET scenarios such as LDACS A2A this may be preferred over CSMA/CA, and it had not been implemented for OMNeT++.

This has been realized through a global `TdmaScheduler` entity. Users are equipped with a custom Network Interface Card (NIC) that provides a `TdmaMac` sublayer. The `TdmaScheduler` then operates as shown in Fig. 1: upon simulation start, all users with a `TdmaMac` sublayer register themselves at the `TdmaScheduler`. Whenever a `TdmaMac` has data to transmit, it notifies the `TdmaScheduler` about its current buffer status, which is the number of packets it is currently waiting to transmit. The `TdmaScheduler` is configured with a TDMA frame size; at the start of a frame, its schedule is computed. In the provided implementation, slots within a frame are allocated to those users that have reported a communication need in a round-robin fashion, while more sophisticated schedule computations are easily realized, which could take fairness over time or throughput into account. The computed schedule is then distributed to the users' `TdmaMac`s, which consequently schedule their respective transmissions.

2.4 Trace-based Radio Model

The OMNeT++ simulator provides a multitude of Physical (PHY) layer radio models already, from simple `UnitDiskRadio` to more advanced models with modulation implementations. However, the realistic modeling of the radio channel can become significantly more complicated than the provided implementations. In fact, such channel models can require such computational

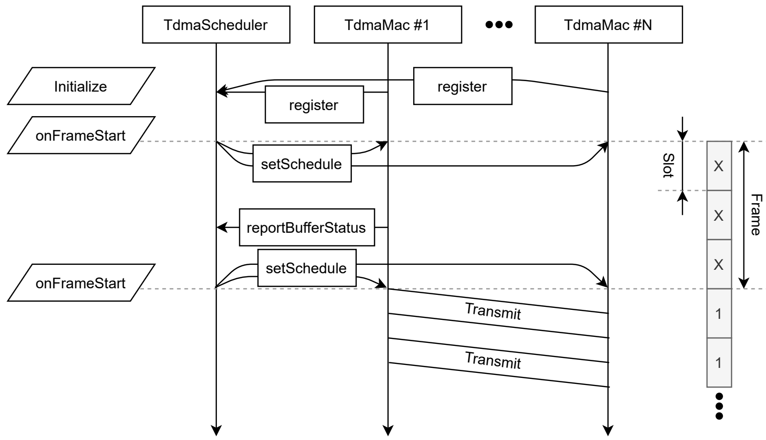

Figure 1: Flow chart of the provided idealized TDMA MAC protocol.

effort that the evaluation of *just* this model for communication between *just* two users in many different constellations takes considerable time. When this is the case, then evaluating this model for the simulation of hundreds of users as they traverse the NAC over the course of real-world hours is out of the question due to the sheer computational complexity.

In this scenario, it is preferable to evaluate the channel model for communication over water (which reflects radio waves differently than ground) once, average the results and use this simplified and averaged model to evaluate above-PHY layer protocols. To achieve this, a novel `TraceBasedRadio` model has been implemented, which extends the `UnitDiskRadio` model. Its corresponding trace file maps SNR to a priori computed Packet Error Rate (PER). With this, arbitrarily complicated channel models can be described using a lookup table; admittedly, this decreases the model's precision, but such a channel model is usually evaluated using other means before this step. It should be noted that no interpolation between the given SNR → PER values is done, as the model has been found to behave non-linearly and no fitting interpolation could be identified. The trace file should therefore contain an adequate resolution of these mappings, as the implementation looks for the closest match.

This model is obtaining the SNR similarly to what is done in [4]. The radio horizon $r_{\mathrm{h}}(h_{\mathrm{tx}}, h_{\mathrm{rx}})$ defines the farthest possible point of propagation and it is given as in Eq. 1, where h_{tx}, h_{rx} are the heights of transmitter and receiver respectively.

$$r_{\mathrm{h}}(h_{\mathrm{tx}},\, h_{\mathrm{rx}})\,[\mathrm{km}] = 130.4(\sqrt{h_{\mathrm{tx}}\,[\mathrm{km}]} + \sqrt{h_{\mathrm{rx}}\,[\mathrm{km}]}). \tag{1}$$

The Free-Space Path Loss (FSPL) denoted by $L_p(d, f, h_{\mathrm{tx}}, h_{\mathrm{rx}})$ is then found as in Eq. 2, where d is the distance between the transmitter and the receiver and f is the transmission frequency; we assume that $L_{\mathrm{p}} \to \infty$ beyond the radio horizon.

$$L_p(d, f, h_{\mathrm{tx}}, h_{\mathrm{rx}})\,[\mathrm{dB}] = \begin{cases} 20\log_{10}(d\,[\mathrm{km}]) + 20\log_{10}(f\,[\mathrm{MHz}]) + 32.4478\,[\mathrm{dB}], & \text{if } d < r_{\mathrm{h}}. \\ \infty, & \text{else.} \end{cases} \tag{2}$$

The received power P_{rx} is then found from Eq. 3, where P_{tx} is the transmission power, G_{tx} and G_{rx} are the transmitter and receiver gains respectively and L_{tx} and L_{rx} represent the transmitter and receiver losses respectively.

$$P_{\mathrm{rx}}\,[\mathrm{dBm}] = P_{\mathrm{tx}}\,[\mathrm{dBm}] + G_{\mathrm{tx}}\,[\mathrm{dBi}] - L_{\mathrm{tx}}\,[\mathrm{dB}] + G_{\mathrm{rx}}\,[\mathrm{dBi}] - L_{\mathrm{rx}}\,[\mathrm{dB}] - L_p(d, f, h_{\mathrm{tx}}, h_{\mathrm{rx}})\,[\mathrm{dB}] \tag{3}$$

Finally, the SNR of a communication link is found using Eq. 4, where F_N is the noise figure, N_0 is the thermal noise density and B is the receiver bandwidth.

$$\mathrm{SNR}\,[\mathrm{dB}] = P_{\mathrm{rx}}\,[\mathrm{dBm}] - \left(F_N\,[\mathrm{dB}] + N_{\mathrm{o}}\left[\frac{\mathrm{dBm}}{\mathrm{Hz}}\right] + 10\log_{10} B\,[\mathrm{Hz}]\right) \tag{4}$$

A provided `TraceBasedReceiver` extends the `UnitDiskReceiver` model by performing this computation, and passing the SNR to a novel `TraceBasedErrorModel`, which queries the trace file-provided lookup table to obtain the closest-matching SNR's mapping to a PER. This trace file is expected to contain a triple of (SNR, PER, Bit Error Rate (BER)) per line. A validation scenario positioned the receiver at $(x = 0\,\mathrm{km}, y = 0\,\mathrm{km}, z = 30\,\mathrm{km})$, and the transmitter at $(x \in \{180, 220, 275, \ldots, 1400\}\,\mathrm{km}, y = 0\,\mathrm{km}, z = 30\,\mathrm{km})$. The distances are chosen to reflect the entire range from certain success to certain failure, and Fig. 2 shows that simulated results are as expected. The variance in simulation results stems from the fact that the lookup table returns the probability of successfully receiving a packet; a random number is then drawn to determine the actual outcome of this transmission attempt, and so the observed PER meets the trace file-provided one on average with some small variance.

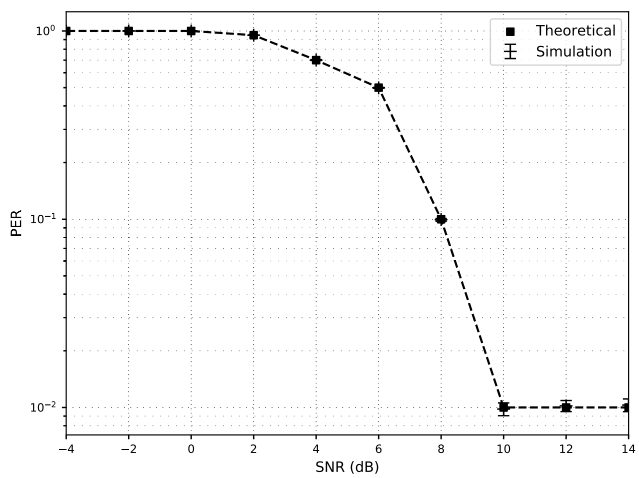

Figure 2: A validation scenario compares expected PER to the one observed through simulation using the provided trace-based radio model.

3 Results

An exemplary evaluation scenario is visualized in Fig. 3. It aims to incorporate all previously described aspects into one simulation model, so that an adaption to other scenarios is easily achieved. In it, a particular OCA is controlled by a ground station positioned in its center. Upon entering or leaving the OCA's range, all aircraft are required to communicate the respective event to the ground station with some pre-defined control message. Simulations have been performed using OMNeT++ v5.6.2 and INET v4.2.5. The simulation parameters are given in Table 1.

The number of received packets at the ground station is evaluated in Fig. 4. As would be expected, the number of *sent* packets is exactly twice the number of users: one packet for OCA

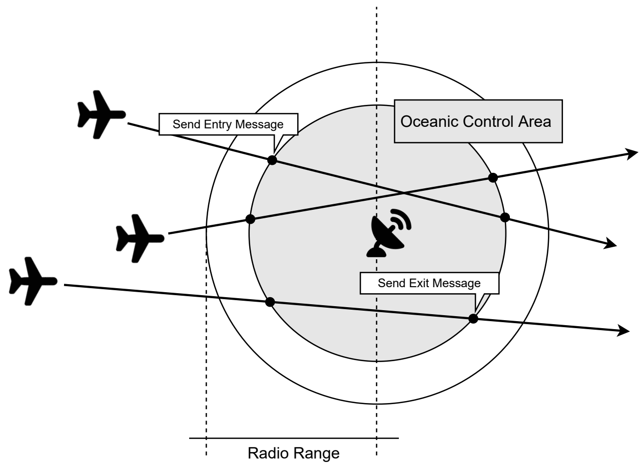

Figure 3: Evaluation Scenario

Number of users	$n \in \{100, 200, \ldots, 500\}$
MAC	Idealized TDMA
TDMA slot duration	10 ms
TDMA number of slots	10 slots
TDMA retransmission attempts	0
Radio model	`traceBasedRadioModel`
Radio range	400 km
OCA range	370.4 km
Number of runs	10
Simulation time	10 000 s

Table 1: Simulation parameters of the exemplary aeronautical MANET scenario.

entry and one for OCA exit. The number of *received* packets is 10 % smaller, which is due to the chosen OCA range at 370.4 km, which translated to a SNR of 8 dB and thus a PER of 10 % as shown in Fig. 2, and which explains the gap between sent and received packets of 10 % in Fig. 4.

4 Conclusion

Trace-based simulation has, in this paper, been motivated by the evaluation of LDACS A2A. In this case, abundant real-world data is available, which presents the opportunity of simulating a communication system under realistic circumstances. In particular, LDACS A2A is going to be utilized for ATC and safety-related applications, where message generation is clearly defined through trigger events. We have provided a tutorial-style summary of how such a scenario can be simulated. Real-world mobility data presents the basis, to which a novel data traffic application can bind the generation of messages. An idealized TDMA MAC protocol fills a gap in the OMNeT++ toolbox, as it realizes a TDMA communication system suitable for simulations where effects of a full-fledged MAC should be suppressed. With its oracle-based design, it can be used even for MANETs, where no central coordinator is present, and for aeronautical networks,

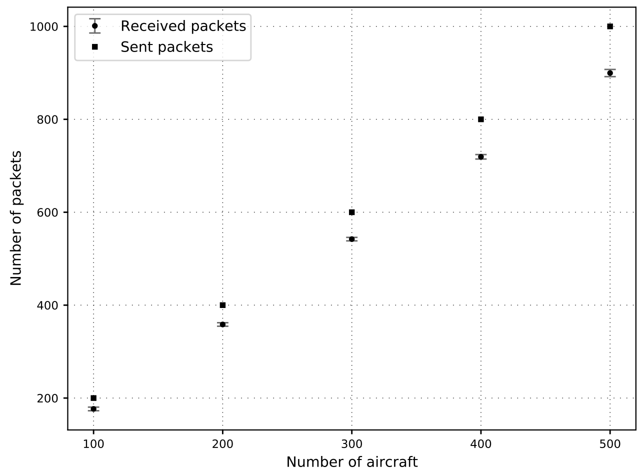

Figure 4: The number of received packets with different number of aircraft considered in the scenario.

where propagation delays prevent CSMA/CA-like approaches. The necessity of including a complicated radio channel model required the implementation of a trace-based radio model for the OMNeT++ simulator. It averages channel behavior by mapping SNR to PER, and so provides an efficient integration of behaviors that usually take considerable computational effort to model.
The presented evaluation scenario binds all of these aspects together. First, the mobility-determined event of entering or leaving an OCA triggers the generation of corresponding control messages. Moreover, the idealized TDMA allocates transmission slots to users and so prevents interference. Additionally, the trace-based radio model has been shown to model a priori defined PERs accurately.
All implemented modules are available under open licenses. They are released in such a way that future research into trace-based scenarios benefits, as the simulation model and components are easily adaptable. The trace-based data traffic application is implemented in [9], the TDMA module is implemented in [10], the radio model in [11] and the example simulation model in [12]. The exemplary scenario was chosen in such a way that it is easy to understand as well as verify. In future work, the trace-based radio model should support BER instead of just the PER, and it should work with Signal-to-Interference-plus-Noise Ratio (SINR) instead of just SNR. In particular, an extension to a radio model that understands multiple, orthogonal frequency channels is foreseen, where simultaneous transmissions within *one* channel should cause interference upon each other, but transmissions in *different* channels should not.

5 Acknowledgments

This work was partially funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) as part of the *IntAirNet* project with reference number 20V1708F.

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