A Delay Model for Satellite Constellation Networks with Inter-Satellite Links

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***Abstract*—Within this paper we examine a non-geostationary satellite constellation network with inter-satellite links (ISLs) for global air traffic control (ATC) and air passenger communication (APC). More specifically, an analysis is done to investigate the impacts of different routing policies on the end-to-end delay, and a general model describing the delays is developed. All considerations are based on a Galileo-like satellite constellation network and real global flight data of all commercial flights during one day**

I. Introduction

This work contributes to the development of a possible future global air traffic management system for migration from the current analogue voice systems towards a digital communication network, relying primarily on data exchange. Because of obvious safety requirements such a system has to guarantee quality of service (QoS) for the air traffic services (ATS) in terms of maximum delay and guaranteed bandwidth.

In our case, the satellite constellation assumed is a fictive Galileo medium earth orbit (MEO) constellation with permanent ISL topology as shown in Fig. 1. In other words: we assume that the Galileo satellites do not only provide a navigation service, but also have a communication payload enabling global (aeronautical) communication [1]. This constellation comprises 30 satellites in a Walker constellation with three inclined planes (56°) and 10 satellites per plane. Each plane will have 9 operational satellites plus one inactive in case of failures which is not considered in our simulations. The period is 14 h 4 min 41 s, for an orbit altitude of 23,222 km. Each satellite has four ISLs: two intra-orbit ISLs (links between satellites in the same plane), and two inter-orbit ISLs (links between satellites in neighboring planes).

Two routing policies are considered within this paper. The first one (policy 1) tries to minimize the number of handovers at the up and downlink (UDL) segment by selecting the satellite which shows the maximum remaining visibility time[2], whereas the second policy (policy 2) tries to minimize the number of hops at the ISL segment, which can lead to many handovers at the UDL segment. Both policies cannot be applied at the same time. In order to find a suitable sequence of satellites for establishing a path between the ingress point (the origin) and the egress point of the satellite system (the destination), the Dijkstra algorithm [3], [4] is used for computing the shortest path i.e. minimizing the delay.

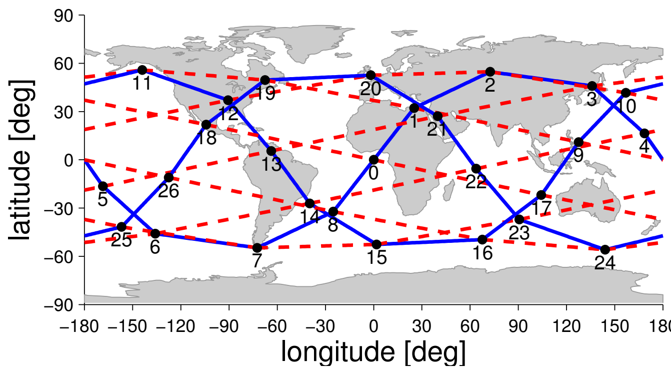

Fig. 1. Snapshot of the fictive Galileo ISL topology.

For our simulations we use a real traffic scenario. It comprises the worldwide flights for one day (May 21st 2007) which have been extracted from a worldwide flight database [5], [6]. In this scenario, only scheduled passenger flights are considered without military flights, helicopters, cargo and general aviation. This database contains 73,477 flights with departure/arrival airports, departure/arrival times, aircraft type and number of seats.

For the generation of data traffic, a sophisticated traffic model has been developed in [6]. Within this model, a range of effects has been considered like the daytime dependence of user activity, correlation factors among different services, seating classes and aircraft types etc. Following this, a traffic distribution model has been developed in [7], which assumes two gateways per continental region, resp. twelve gateways worldwide.

II. Assumptions

The scenario and resulting simulation environment is rather complex, and therefore several assumptions had to be made for the analysis of the end-to-end delay:

- In our model three sorts of traffic exist: ATS voice, APC voice and data traffic. ATS voice has the highest priority.
- Only ATS voice communication and no ATS data is used in the analysis. So the overall packet categories which have to be considered are VoIP packets (for ATS and APC voice) and IP packets (APC data). For IP packets a

length of 1500 Bytes has been assumed, for VoIP packets 100 Bytes.

- When arriving in a satellite, packets are enqueued and transmitted just after scheduling. Packets are always transmitted one-by-one. For this reason the satellites have to obtain buffers, queues and scheduling mechanisms, which all impact the total delay. Depending on the load of the satellite, the time in the queue may be longer or shorter. For simplicity it is assumed in the simulations that there exist three different queues in the satellite: one dedicated to ATS voice, one for APC voice and one for APC data. The policy for scheduling is a strict priority scheme, whereas ATS packets are always transmitted first, APC voice packets are transmitted with the next higher priority, followed by all data packets, as can be seen on Fig. 2. The data rate of the output link is chosen to 270 Mbps, corresponding to the maximal rate that has been observed on the ISLs with the continental distribution model and for all policies.

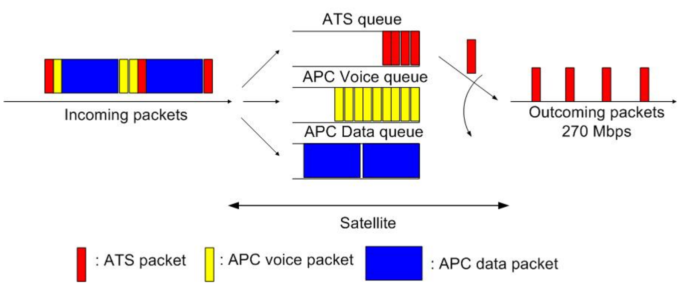

Fig. 2. Principle of the queuing policy.

- In total each satellite has four ISLs plus one uplink (UL) and one downlink (DL). Moreover the traffic on the forward link has to be differentiated from the traffic on the return link, so each link is bi-directional. This means that in reality each satellite has 12 links (4× inter orbit, 4× intra orbit, 2× UL, 2× DL). Although satellites with this functionality appear to be rather complex we believe that optical inter-satellite communication will be the key because optical transmitters are very compact with low power consumption. With technology available today the onboard-switching should not be a major obstacle.
  For complexity reasons it is not possible to simulate three queues for each link because this would mean that each satellite has more than 30 different queues. Consequently the queues were setup just for the outgoing ISLs as Fig. 3 shows. Queues for the DL are not considered in the simulations done here; omitting the incoming queues does not have significant influence on the simulation results since these queues are no bottlenecks for the system. In order to further reduce the complexity of the problem, the model only considers the queue waiting time in the first satellite. This means that it is implicitly assumed that sufficient bandwidth in the ISL segment is available so no further queuing delay is introduced along the way.
- Furthermore the propagation delay for each part of the route within the ISL segment is considered in the simulations.

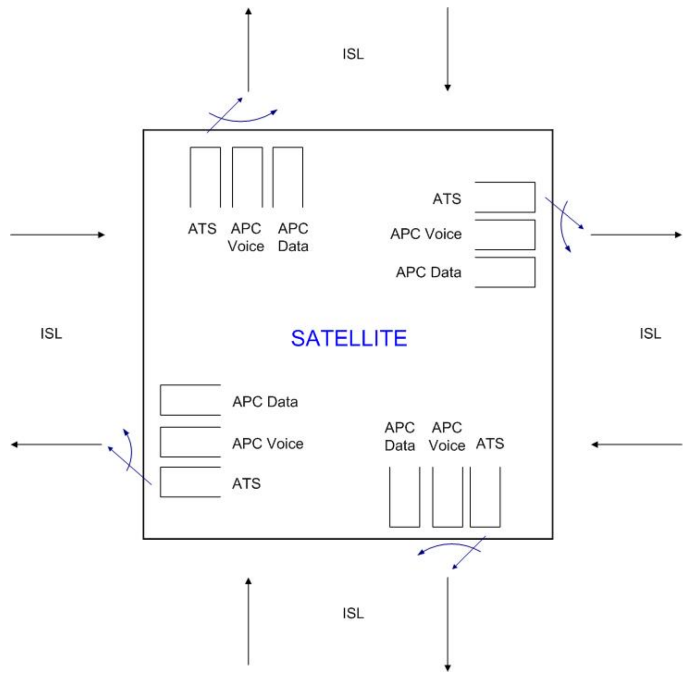

Fig. 3. Queues in a satellite.

- A processing delay is considered for each hop along the ISL path. The processing delay is assumed to be in the order of 1 ms.
- The propagation delay from the transmitting end system (aircraft or gateway) to the first satellite and from the last satellite to the receiving end system is also included in the simulations. For this delay, 77 ms are chosen which corresponds to the propagation delay for a MEO satellite (23,222 km, sub-satellite point).
- A handover can impact the total variation of the delay within the ISL constellation. This is because the path from ingress to egress point may change during a connection. This can cause an overlap of packets (or gap) because the new path can be shorter (or longer) as can be seen on Fig. 4. I.e. it may happen that the last packet of a transmission arrives before the previous packets if the new path got shorter. For this study it is assumed that all preceding packets have to be received before the last packet is considered received, too.

With these assumptions, we analyze the transmission delay of packets and develop a general channel model of the delay.

III. Delay Analysis

Fig. 5 shows one representative example of how the delay variation develops over time for a connection between two satellites on the return link with policy 1: all previously described effects can be seen. The connection between satellites 10 and 14 is an arbitrary choice but this example shows the most significant delay variation.

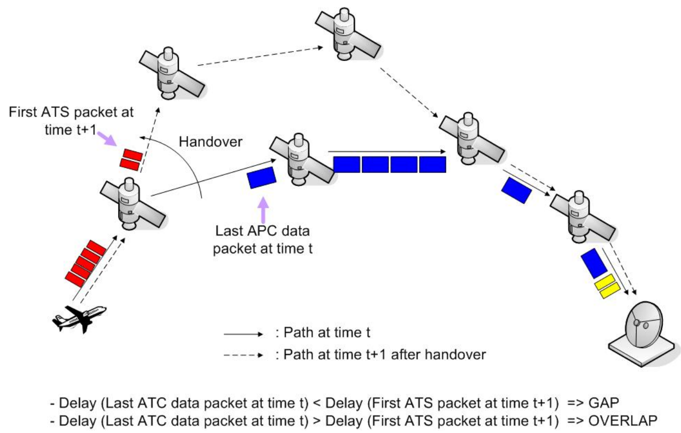

Fig. 4. Delay caused by a handover.

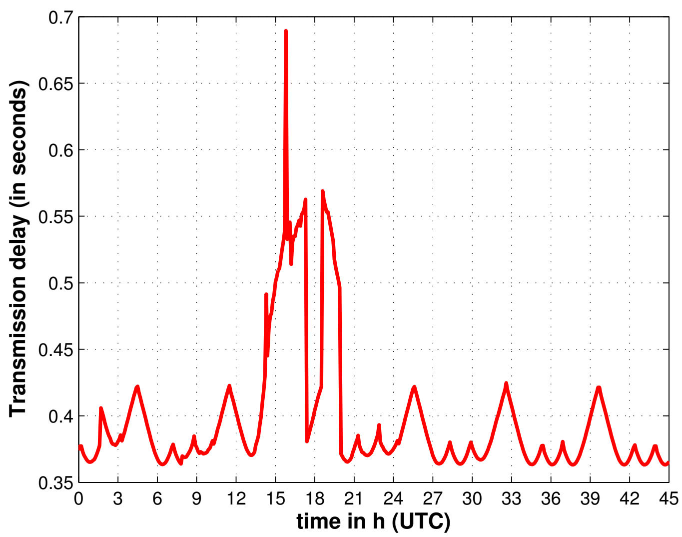

Fig. 5. Transmission delay with policy 1 between satellites 10 and 4.

In the time frame between 24:00 coordinated universal time (UTC) and 45:00 UTC the variation of the delay is periodic which is caused by the deterministic movement of the satellites within the constellation. In the time frame between 13:00 UTC and 20:00 UTC, the additional impact of the queue waiting time can be seen. At this time satellite 10 moves across the North Atlantic region, at the same time many trans-atlantic flights from the U.S. to Europe and vice versa have to be served, so the two peaks indicate that satellite 10 has to handle a lot of data as can be seen on Fig. 6. Finally the narrow and high peak around 16:00 UTC shows the impact of the handover delay. To see this effect, a huge amount of data has to be sent at this time and a handover with a new shorter path (in terms of distance) than the previous one has to occur.

IV. Markov Model

This section describes how the observed delay variation can be modeled by a statistical Markov chain process. The following study is realized for policy 1 and the forward link, but the results are identical for the three other cases (policy 1 and return link, policy 2 and forward link, policy 2 and return link).

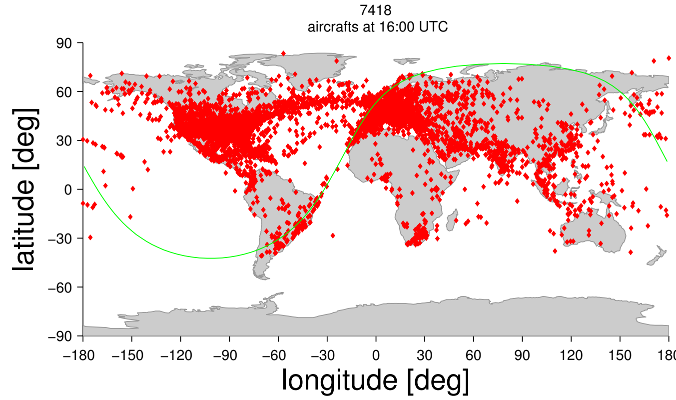

Fig. 6. Aircraft distribution and footprint of satellite 10 at 16:00 UTC.

For this purpose, the delay between all possible combinations of satellites has been computed. The total delay is composed of effects caused by queuing, continuously changing propagation delay (inter-orbit ISLs experience a periodic length variation), and due to handovers. While the queuing delay is stochastic, the delays due to ISLs and handovers are deterministic since they are related to the constellation.

In order to find out whether the stochastic process can be modeled better by a probability density function (PDF) or a Markov chain, an analysis of the autocorrelation behavior has been done. As explained in [8], if the half maximum width of the main peak of the autocorrelation is smaller than one time step, the process can be considered memoryless and can be represented by a PDF. On the contrary, if this half maximum width is bigger than one time step, a Markov chain seems more appropriate to describe the process because it will be with memory. Fig. 7 shows the histogram of the half width of the autocorrelation function of the queuing delay for all satellite constellations for policy 1 and the forward link.

From this analysis it can be seen that the minimum width of the autocorrelation is 6 time steps with 6 minutes per time step. This means that the process has memory and that it may be possible to model it by a Markov chain.

A stochastic process can be modeled as a Markov process if it complies with the Markov property which says that the conditional probability distribution of future states of the process (given the present and all past states) depends only upon the present states and not on any past states. Moreover, it is also important in this case to check the stationarity of the process. Stationarity is a necessary but not a sufficient condition, meaning that all Markov chains are stationary but not all stationary process can be modeled by Markov chains.

However these criteria are theoretical and can not be easily verified in our approach because of e.g., the fact that we have a limited number of samples. Thus it is impossible in reality to prove that our process is a Markov process.

Nevertheless statistical tests have been developed in order to realize approximations of Markov processes. Reference [9]

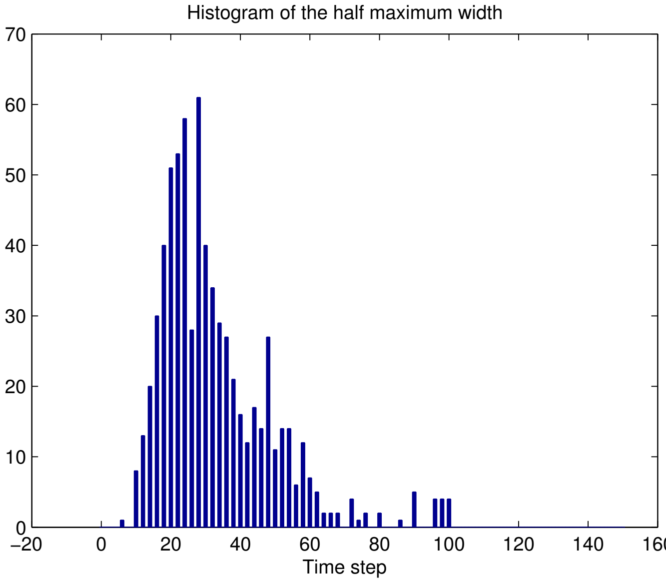

Fig. 7. Histogram of the half maximum width of the autocorrelation for policy 1 and the forward link.

mentions two of these tests, and notably a statistical test on the geometrical distribution of the dwell times in each state. Processing this test does not by itself guarantee that the process is Markovian, since this property is a necessary but not a sufficient condition. Therefore, an assessment of the Markov character of a process based on this statistical test is regarded as an approximation. Thus if for each state the distribution is decreasing exponentially, we will be able to say that our process can be regarded as an approximation of a Markov process, which verifies the stationarity and the Markov property.

For the Markov chain model eight states as shown in Table I have been defined. For the selection of the intervals, the PDF of the occurring delays has been used to have on the one hand a fine granularity avoiding states which are never or only seldom used, and on the other hand keeping the total number of states reasonable.

TABLE I
MARKOV CHAIN STATE DEFINITIONS.

State	Delay intervals
1	0 - 0.5 ms
2	0.5 ms to 1 ms
3	1 ms to 2 ms
4	2 ms to 5 ms
5	5 ms to 10 ms
6	10 ms to 50 ms
7	50 ms to 0.1s
8	0.1 s to 1 s

To calculate the transition probabilities between the states, the delay values for each satellite combination have been quantized into the states according to the delay intervals shown in Table I. Then the probabilities to switch between two states have been computed from all the states transitions.

In order to study if our process verifies the statistical test, the geometrical distribution of the dwell time has been computed. For this it is necessary to know the probability to stay in a specific state for each time step. Eq. 1 shows the probability to stay in state M during N time step:

$$P(t=N) = P(S_M) \cdot P(S_M, S_M)^{N-1} \cdot (1 - P(S_M, S_M)) \quad (1)$$

with $P(S_M, S_M)$ the probability to stay in state M when we are already in state M.

Fig. 8 shows the results for the distribution of the dwell times in each state.

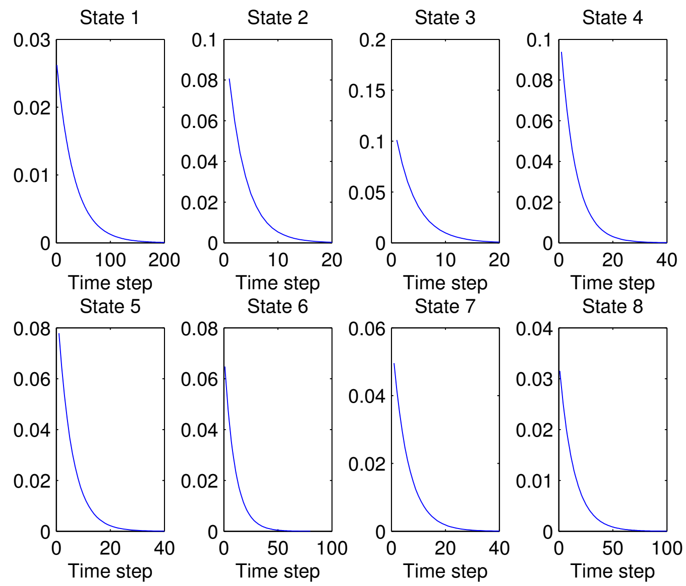

Fig. 8. Geometrical distribution of the dwell time for each state.

As can be seen here, all distributions decrease exponentially, meaning that a Markov process is a good approximation of the delay process. Fig. 9 shows the resulting Markov chain model with the eight states as shown in Table I.

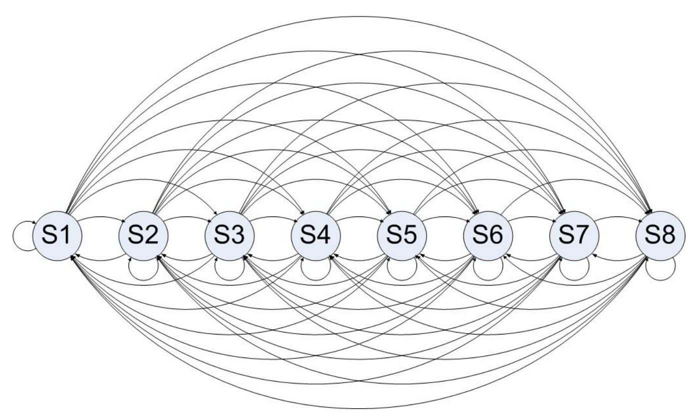

Fig. 9. Markov chain model for the delay modeling.

Table II through Table V show the transition probabilities for both policies and for forward link and return link. It can be observed that in each case the probability to stay in the same state is very high compared with the probability to leave the state.

TABLE II
TRANSITION PROBABILITIES FOR POLICY 1 AND THE FORWARD LINK.

	S1	S2	S3	S4	S5	S6	S7	S8
S1	0.9697	0.0144	0.005	0.005	0.0028	0.0024	0.0004	0.0003
S2	0.1243	0.74	0.1002	0.0211	0.0066	0.0066	0.0004	0.0008
S3	0.0309	0.0873	0.7706	0.0902	0.0091	0.0096	0.0012	0.0011
S4	0.0167	0.0094	0.059	0.8354	0.0649	0.0118	0.001	0.0018
S5	0.0118	0.0028	0.0059	0.0821	0.8288	0.0646	0.0012	0.0028
S6	0.0055	0.0028	0.0035	0.0077	0.0483	0.9038	0.0215	0.0069
S7	0.0034	0.0001	0.0042	0.0096	0.0078	0.0907	0.8412	0.043
S8	0.0035	0.0003	0.0025	0.0029	0.0035	0.0124	0.0462	0.9287

TABLE III
TRANSITION PROBABILITIES FOR POLICY 1 AND THE RETURN LINK.

	S1	S2	S3	S4	S5	S6	S7	S8
S1	0.9715	0.0161	0.0046	0.0042	0.0021	0.0011	0.0002	0.0002
S2	0.1137	0.7779	0.0869	0.0133	0.0056	0.002	0.0003	0.0003
S3	0.0284	0.0857	0.786	0.0868	0.0068	0.0048	0.001	0.0005
S4	0.0137	0.0064	0.0545	0.8658	0.0525	0.0053	0.001	0.0008
S5	0.0112	0.0035	0.0063	0.0809	0.8414	0.0531	0.002	0.0016
S6	0.0045	0.0025	0.0055	0.0093	0.0491	0.9104	0.0165	0.0022
S7	0.0063	0.0012	0.0036	0.0086	0.0033	0.0905	0.8573	0.0292
S8	0.0042	0.0011	0.0038	0.0033	0.0062	0.0271	0.0387	0.9156

TABLE IV
TRANSITION PROBABILITIES FOR POLICY 2 AND THE FORWARD LINK.

	S1	S2	S3	S4	S5	S6	S7	S8
S1	0.9583	0.0168	0.0079	0.0083	0.0043	0.0037	0.0002	0.0005
S2	0.1651	0.6612	0.1093	0.0334	0.0182	0.0116	0.0008	0.0004
S3	0.0548	0.0973	0.6913	0.1157	0.0203	0.0156	0.0031	0.0019
S4	0.0318	0.014	0.0828	0.7653	0.0796	0.0198	0.0022	0.0045
S5	0.0186	0.0085	0.0136	0.0986	0.7568	0.0987	0.0023	0.0029
S6	0.0109	0.0047	0.0043	0.0145	0.0651	0.8712	0.0225	0.0068
S7	0.0081	0.0011	0.0036	0.0093	0.0085	0.1306	0.7713	0.0675
S8	0.0053	0.0017	0.0038	0.0077	0.0063	0.0241	0.0619	0.8892

TABLE V
TRANSITION PROBABILITIES FOR POLICY 2 AND THE RETURN LINK.

	S1	S2	S3	S4	S5	S6	S7	S8
S1	0.9604	0.0191	0.009	0.0071	0.0023	0.0018	0.0002	0.0001
S2	0.1542	0.6923	0.1056	0.0279	0.0134	0.0045	0.001	0.0011
S3	0.0479	0.0939	0.7334	0.1024	0.0117	0.0092	0.0004	0.0011
S4	0.0259	0.0152	0.0788	0.7987	0.0699	0.0094	0.0013	0.0008
S5	0.0161	0.0081	0.0121	0.1157	0.7659	0.0777	0.0026	0.0018
S6	0.0109	0.0033	0.0065	0.0152	0.0648	0.8746	0.0207	0.004
S7	0.0057	0.0023	0.0074	0.0047	0.0077	0.1268	0.8207	0.0247
S8	0.0052	0.0036	0.0013	0.0068	0.0136	0.0308	0.0798	0.8589

Finally Fig. 10 shows an example for the delay variation which is produced by the developed Markov chain model.

V. CONCLUSION

In this work, a Markov chain model was developed which allows the statistical modeling of the transmission delay of a packet within the ISL network. It has been shown that the statistical delay variations (without the deterministic changes due to the constellation) can be appropriately described by a Markov chain model. Moreover the numerical values for the state transitions were computed to allow to a direct implementation of this delay model. It is possible to use this model to analyse the impact of different routing policies on the system performance in terms of transmission delay and signalling overhead caused by hand-overs.

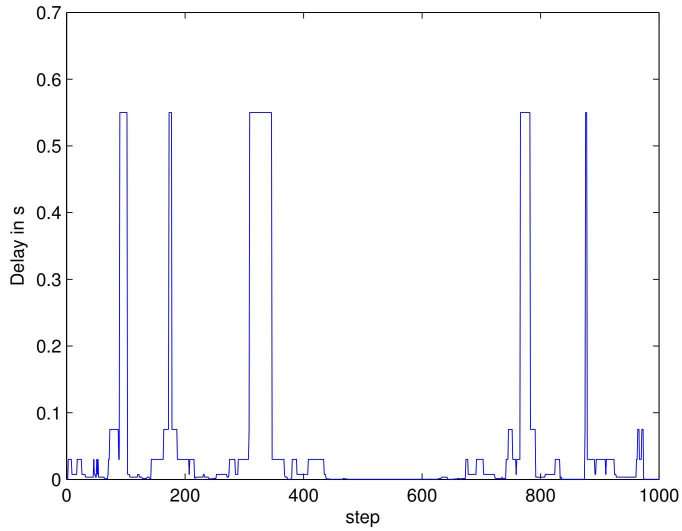

Fig. 10. Exemplary output of the developed Markov chain model (policy 1, forward link).

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