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Cooperative Hybrid Land Mobile Satellite–Terrestrial Broadcasting Systems: Outage Probability Evaluation and Accurate Simulation

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Abstract Next generation communication networks incorporate Land Mobile Satellite (LMS) systems in order to provide greater areas of coverage and higher throughput for specific applications. Cooperation between satellite communication networks and terrestrial relays is or increasing the system's performance and availability. In this paper, the outage performance of a cooperative hybrid satellite and terrestrial system configuration is analytically evaluated assuming that the satellite links suffer from shadowed Rician fading, while the terrestrial link suffers from the Nakagami-m fading. Two cooperative relaying strategies are examined and the final formulas for the calculation of the outage probability are given. Moreover, a block diagram for the generation of time series for the reliable simulations of the outage probability of the cooperative hybrid land mobile satellite systems is given. The theoretical results and the simulation results almost coincide. Moreover, extended numerical results investigate the impact, of different shadowing conditions and more generally of the satellite links elevation angles, on the overall cooperative LMS system performance.

Keywords Land mobile satellite (LMS) · Cooperative diversity · Radio relays, Hybrid satellite–terrestrial · LMS channel models · Time series generator

1 Introduction

Multiple Input Multiple Output (MIMO) antenna techniques have been recently proposed in Land Mobile Satellite (LMS) systems in order to increase the transmission rates, the availability and generally to enhance the capacity and to exploit the interference. Mobile

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Satellite Systems are able to provide large coverage at mobile users and also achieving high data rate transmission at low cost [1] in navigation, communications and broadcasting applications. Moreover, cooperative techniques, which can be seen as virtual MIMO systems, have been extensively used to increase the system performance of terrestrial wireless networks [2] offering spatial diversity. Cooperation can be applied to LMS in terms of hybrid satellite-terrestrial systems where terrestrial relays forward the information broadcasted by the satellite to the final destination [3], operating as assisted gap-filers. The cooperative relaying scenarios between sources and destinations incorporating satellite part are analytically described in [3].

A well accepted channel model for LMS link that suffers from multipath and shadow fading has been proposed in [4]. Multipath fading is caused due to scattering in the mobile terminal environment, which results in different propagation paths. Therefore, the received signal consists of a Line-of-Sight (LOS) component and the scatter components and its envelope can be modeled as a Rician random variable. Moreover, the LOS component may suffer from blockage due to buildings, trees, hills or mountains resulting in a shadowed Rician channel where the amplitude of the LOS component is a Nakagami-m random variable [4]. Consequently, the power of the LOS component is considered that follows the Gamma distribution.

In [5], the uplink case of a fixed relaying (FR) [2] LMS cooperative system using a terrestrial relay is studied. The source-satellite channel is modeled following the shadowed Rice distribution [4], but the relay-satellite channel is assumed to be non-shadowed following the Rician distribution. The source-relay terrestrial channel follows the Rayleigh distribution. Very recently, the performance of hybrid satellite terrestrial systems considering beamforming, and combining techniques has been investigated in [6–9]. Interesting analytical results of the cooperative network are presented in [6–9].

In a preliminary work we have investigated the outage performance of a cooperative scheme using Selection Relaying protocol [10]. In this work, the outage performance of the downlink of a broadcasting cooperative LMS system with a terrestrial regenerative relay is evaluated employing for both the FR and the Selection Relaying (SR) cooperative protocols. Both LMS channels suffer from shadowed Rice fading [4], while the terrestrial link suffers from Nakagami-m fading [11]. The assumptions for the channel are more realistic comparing to previously published works. The outage probability of the cooperative LMS system is analytically evaluated in terms of easily calculated integrals, while the effect of the various shadowing environments (light, average or heavy shadowing) on the system performance is studied extensively.

Moreover in this paper, an accurate simulation framework for hybrid cooperative satellite schemes is proposed and used in order to validate our results. The analytical results for outage probability are verified through the proposed accurate simulation framework.

The remainder of the paper is structured as follows: Sect. 2 presents the hybrid cooperative satellite terrestrial scheme under consideration. In Sect. 3 the outage performance of the two relay protocols in the proposed cooperative scheme is evaluated. In Sect. 4, the proposed accurate simulation framework for the generation of time series of the received complex envelope of the corresponding cooperative links is presented. Section 5 presents extensive numerical results and some significant remarks on them. Finally, the work is concluded in Sect. 6.

2 Hybrid Cooperative Satellite Terrestrial Scheme

The configuration of the hybrid cooperative LMS system is shown in Fig. 1. The geometrical characteristics of the scheme are also given in Fig. 1. The satellite **S** (source) broadcasts

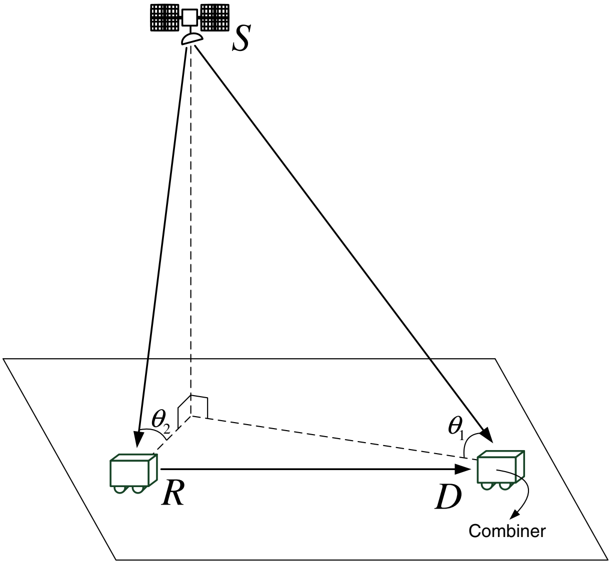

Fig. 1 Cooperative land mobile satellite system scheme

the same information signal to both mobile satellite terminals, namely the relay **R** and the destination **D**. The mobile satellite terminal **R** acts as a regenerative relay and uses the decode-and-forward technique in order to retransmit the received signal to the mobile satellite terminal **D**. The destination **D** combines the two signals received by direct transmission and through the cooperative relay, using the maximal ratio combining (MRC) technique [12]. In this work, we consider MRC technique since is the most efficient one.

Both LMS channels are considered that suffer from shadowed Rice fading [4], but with different statistical parameters in general, while the corresponding terrestrial link suffers from Nakagami-m fading [11] and therefore its signal power follows the Gamma distribution. The elevation angles of the **S-D** and **S-R** LMS slant paths are denoted as θ_j (deg) , $j = 1, 2$. Since the terrestrial path length is much smaller comparing to the satellite slant path lengths, the two satellite links are considered to be parallel and this results in almost equal elevation angles $\theta_1 = \theta_2$. This assumption does not limit the general applications of the results. Moreover this scenario can be considered for cooperative applications of satellite nomadic users [3].

3 Outage Performance Analysis

In this section, analytical straightforward expressions are given for the hybrid cooperative satellite terrestrial scenario described in Sect. 2. The outage probability of a LMS system is defined as the fraction of time where the total mutual information I (bits/ (Hz · sec)) does not exceed a threshold $I_{th.norm}$:

$$P_{out} = P\left(I < I_{th.norm}\right) \tag{1}$$

3.1 Fixed Relaying (FR) Protocol

In the FR protocol, R always retransmits the received signal and therefore this protocol is limited by the **S-R** satellite link as it is shown in [2]. The mutual information of the SR protocol describing the outage event in (1) is given:

$$I_{FR} = \frac{1}{2}\min\left\{\log_2\left(1+\gamma_2\right), \log_2\left(1+\gamma_1+\gamma_3\right)\right\} \tag{2}$$

In (2), γ_j, $(j = 1, 2, 3)$ correspond to the **S-D**, **S-R** and **R-D** Signal-to-Noise Ratio (SNR), respectively. The rate normalized threshold $I_{th.norm}$ incorporates the spectral inefficiency of the two time slots used by the cooperative protocol which is described by the term 1/2 in (2). The threshold γ_{th} in (2) is related to $I_{th.norm}$ and to an equivalent rate normalized SNR threshold with [13]:

$$\gamma_{th} = 2^{2I_{th.norm}} - 1 = 2^{2\log_2(1+\gamma_{th.norm})} - 1 = \gamma_{th.norm}^2 + 2\gamma_{th.norm} \tag{3}$$

Using (1), (2), (3) the shadowed Rice distributions $f_{\gamma_1}(\gamma_1)$ and $f_{\gamma_2}(\gamma_2)$[4], the Gamma distribution $f_{\gamma_3}(\gamma_3)$ and the incomplete and complete gamma functions $\Gamma(\cdot,\cdot)$ and $\Gamma(\cdot)$ respectively, the outage probability can be calculated by:

$$\begin{aligned} P_{out} &= P\left(\gamma_2 < \gamma_{th}\right) + P\left(\gamma_2 \geq \gamma_{th}\right) P\left(\gamma_1 + \gamma_3 < \gamma_{th}\right) = \\ &= \int_0^{\gamma_{th}} f_{\gamma_2}\left(\gamma_2\right) d\gamma_2 \\ &\quad + \int_{\gamma_{th}}^{\infty} f_{\gamma_2}\left(\gamma_2\right) d\gamma_2 \int_0^{\gamma_{th}} f_{\gamma_1}\left(\gamma_1\right)\left(1 - \Gamma\left(m_3, \frac{m_3}{\Omega_3}\left(\gamma_{th} - \gamma_1\right)\right)\Big/\Gamma\left(m_3\right)\right) d\gamma_1 \end{aligned} \tag{4}$$

In equation (4), the parameters of the Gamma distribution of the terrestrial path are denoted as m_3, Ω_3. The shadowed Rice distribution is given in [4] with parameters b_0, m, Ω:

$$f_\gamma\left(\gamma\right) = \left(\frac{2b_0 m}{2b_0 m + \Omega}\right)^m \frac{1}{2b_0} \exp\left(-\frac{\gamma}{2b_0}\right) \cdot {}_1F_1\left(m, 1, \frac{\Omega s}{2b_0\left(2b_0 m + \Omega\right)}\right), \quad \gamma \geq 0 \tag{5}$$

In equation (5), ${}_1F_1(\cdot,\cdot,\cdot)$ is the confluent hypergeometirc function [14].

3.2 Selection Relaying (SR) Protocol

In the SR protocol, **R** retransmits the received signal only in the case where the signal is correctly decoded. If **R** cannot decode the received signal, it does not retransmit it to **D** and the system falls back to direct transmission. The mutual information of the SR protocol, which is not limited by the **S-R** link, describing the outage event in (1) is given:

$$I_{SR} = \begin{cases} \frac{1}{2}\log_2\left(1+\gamma_1\right), & \text{for} \quad \gamma_2 < \gamma_{th} \\ \frac{1}{2}\log_2\left(1+\gamma_1+\gamma_3\right), & \text{for} \quad \gamma_2 \geq \gamma_{th} \end{cases} \tag{6}$$

It should be noted that if **R** fails to decode the received signal, **S** cannot retransmit the same signal in the second time slot too as in [2], due to the large satellite transmission delay.

Using (1), (3) and (6), similarly to the FR case, the outage probability is calculated by:

$$\begin{aligned} P_{out} &= P\left(\gamma_2 < \gamma_{th}\right) P\left(\gamma_1 < \gamma_{th}\right) + P\left(\gamma_2 \geq \gamma_{th}\right) P\left(\gamma_1 + \gamma_3 < \gamma_{th}\right) \\ &= \int\limits_0^{\gamma_{th}} f_{\gamma_2}\left(\gamma_2\right) d\gamma_2 \int\limits_0^{\gamma_{th}} f_{\gamma_1}\left(\gamma_1\right) d\gamma_1 + \\ &\quad + \int\limits_{\gamma_{th}}^{\infty} f_{\gamma_2}\left(\gamma_2\right) d\gamma_2 \int\limits_0^{\gamma_{th}} f_{\gamma_1}\left(\gamma_1\right) \left(1 - \Gamma\left(m_3, \frac{m_3}{\Omega_3}\left(\gamma_{th} - \gamma_1\right)\right) / \Gamma\left(m_3\right)\right) d\gamma_1 \end{aligned} \quad (7)$$

The final expressions (4) and (7) can be easily calculated numerically since they converge very fast due to the monotonically decreasing nature of the integrand functions. The integrand functions are products of probability density functions. More specifically, replacing the infinite limit ∞ with an appropriate positive number results in the desired numerical precision for the outage probability.

4 Accurate Simulation Framework

In this Section, the above proposed formulas for the calculation of the outage probability are validated with accurate time series simulations. We briefly present an accurate simulation framework for the simulation of the time series of the three links that are necessary for the in the cooperative scenario under consideration. More specifically, the generation of time series of the three links of the system geometry given in Fig. 1, the methodology shown in Fig 2a, b is used. For the link between the satellite and the final destination, the channel model is used. In the later model, the received complex envelope is the summation of a Rayleigh phasor and a Nakagami phasor:

$$r(t) = A(t) \exp\left(j a(t)\right) + Z(t) \exp\left(j \zeta_0\right) \quad (8)$$

where $A(t)$ is Rayleigh distributed, $a(t)$ uniformly distributed in $[0, 2\pi]$, $Z(t)$ the amplitude of the direct component which follows the Nakagami distribution and ζ_0 the phase of the direct component, also following uniform distribution in $[0, 2\pi]$. By definition the instantaneous power is considered $r^2(t)$ and the signal-to-noise ratios can be calculated. The two phasors are considered independent, similarly with the Loo channel model [15]. Moreover, the channel is generated for every time slot. In each time slot the Rayleigh distributed amplitudes $(A(t))$ are taken independent, as well as the uniformly distributed random variables of the phase $(a(t))$. The Nakagami distributed random variables $Z(t)$ are considered correlated, since they represent the direct component of the signal which is under shadowing conditions. The autocorrelation of $Z(t)$ is taken from [15]. Although, there are various methods for the generation of correlated Nakagami samples, we use the copulas-based methodology [16,17]. The later method is also used for the generation of the Nakagami time series for the terrestrial link between the terrestrial relay and the destination. Finally, it must be noted that in our analysis, as assumed in the previous Section we consider the fading at the three links independent between them.

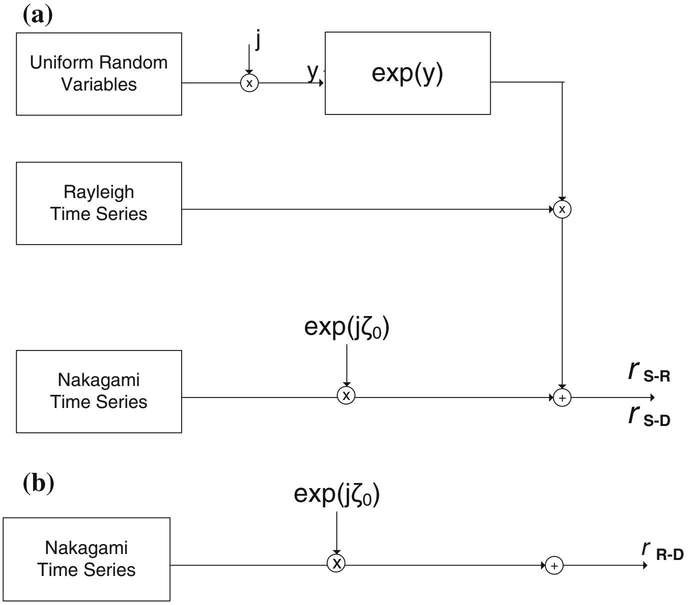

Fig. 2 **a** Block diagram for the generation of time series of the received envelope for the satellite LMS links of the cooperative scheme, **b** block diagram for the generation of time series of the received envelope for the terrestrial link of the cooperative scheme

Table 1 Shadowing parameters

	b_0	m	Ω
Light shadowing	0.158	19.4	1.29
Average shadowing	0.126	10.1	0.835
Heavy shadowing	0.063	0.739	8.97×10-4

5 Numerical Results and Discussion

In this Section, numerical results are presented for the outage performance of a cooperative hybrid satellite-terrestrial system. Unless otherwise stated, the parameters of the satellite shadowed Rice and the terrestrial gamma distributions, taken from [4], are given in Table 1. The relative performance of the single satellite direct link is also considered for comparison.

Firstly, we will verify the proposed analytical results with the theoretical ones. In Fig. 3, we present the outage performance of a Selection Relaying Cooperative LMS and it is compared with the performance of the FR protocol. The corresponding curves from the simulation results are also shown. The simulated and the theoretical results coincide. This is a significant result that shows the validity of the theoretical results and the accuracy of the simulation framework. In the rest Figures we will present results using the theoretical formulas.

The performance of the SR protocol is much better since the performance of the FR protocol is limited by the condition of the **S-R** link. The single satellite performance is also given for comparison. All links suffer from light shadowing and the relevant parameters are given in Table 1. As can be seen by Fig. 3, the FR cooperative protocol has worse performance than the single satellite link for all values of the normalized SNR threshold and for all the corresponding values of outage probability. Therefore, the Selection Relaying protocol has

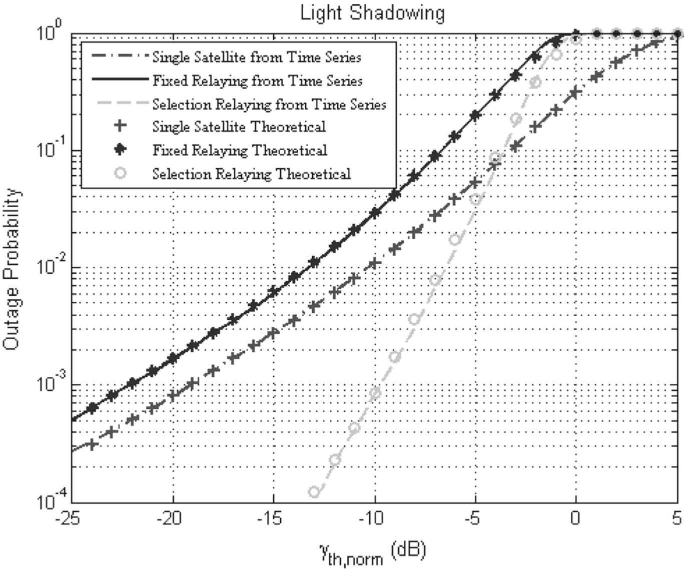

Fig. 3 Outage probability of different cooperative LMS protocols and a single satellite for a light shadowing environment. The outage probability curves from the simulation framework are also shown

to be used in order to increase the performance of the hybrid satellite-terrestrial cooperative system. As it is shown in this Figure, the Selection Relaying protocol outperforms the FR protocol for all values of outage probability. Moreover, Selection Relaying offers significant gain over both the FR and the single satellite systems, especially for small values of outage probability, e.g. about 12 and 9 dB, respectively for outage probability of 10^{-3}.

In Fig. 4, the Selection Relaying cooperative LMS performance is plotted for different values of the satellite elevation angle. The terrestrial link suffers from heavy shadowing taking into account the values of Table 1, while the parameters of the satellite links depend on the elevation angle and they are calculated by the following expressions [4]:

$$\begin{aligned} b_0(\theta) &= -4.7943\cdot 10^{-8}\theta^3 + 5.5784\cdot 10^{-6}\theta^2 - 2.1344\cdot 10^{-4}\theta + 3.2710\cdot 10^{-2} \\ m(\theta) &= 6.3739\cdot 10^{-5}\theta^3 + 5.8533\cdot 10^{-4}\theta^2 - 1.5973\cdot 10^{-1}\theta + 3.5156 \\ \Omega(\theta) &= 1.4428\cdot 10^{-5}\theta^3 - 2.3798\cdot 10^{-3}\theta^2 + 1.2702\cdot 10^{-1}\theta - 1.4864 \end{aligned} \tag{9}$$

As can be seen in Fig. 4, the performance of the hybrid satellite-terrestrial cooperative system increases, as the elevation angle increases. This is expected since higher elevation angles correspond to propagation conditions that suffer from lighter shadowing. Moreover, it can be observed that the value of the elevation angle dramatically affects the cooperative LMS system, since small elevation angles result in very high values of outage probability compared to the outage values of high elevation angles. In addition, the relative SNR gain for a given value of outage probability is smaller between 60° and 80° than between 40° and 60°. Finally, it should be noted that when the terrestrial link suffers from heavy shadowing, the single satellite link outperforms the cooperative one for all the values of the elevation angle.

In Fig. 5, the performance of the cooperative SR LMS is also plotted for different values of elevation angles as in Fig. 3, but for average terrestrial shadowing. The elevation angle has the same impact on the cooperative performance as in Fig. 3. Nevertheless, the propagation conditions of the terrestrial link have a significant effect on the overall cooperative LMS

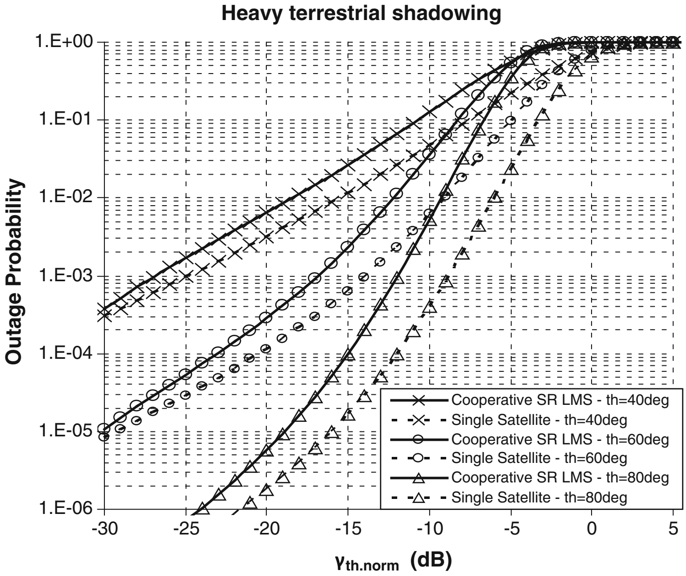

Fig. 4 Outage probability of a selection relaying cooperative LMS system for different elevation angles and heavy terrestrial shadowing

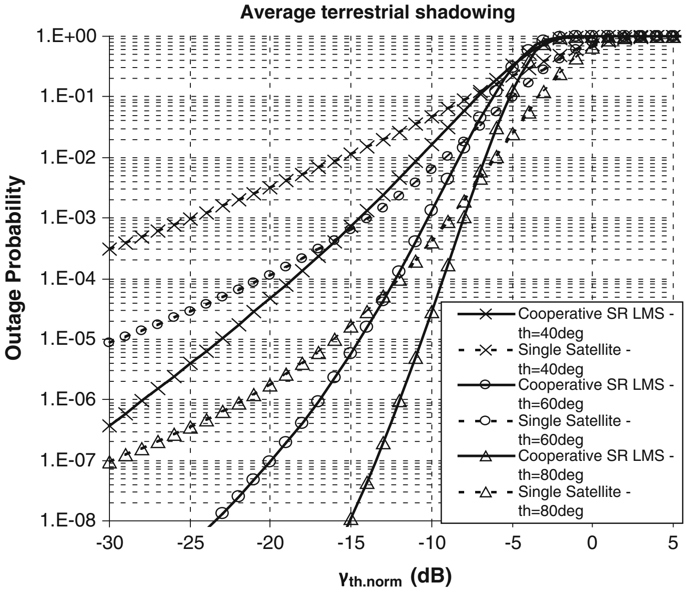

Fig. 5 Outage probability of a selection relaying cooperative LMS system for different elevation angles and average terrestrial shadowing

performance. Comparing Figs. 3 and 4, it can be observed that when the terrestrial link suffers from average shadowing, the cooperative LMS performance improves significantly, even by a factor of 15 dB for a given value of outage probability. In addition, for all values of elevation angle the cooperative system outperforms the single satellite system. Finally, for light terrestrial shadowing conditions, not shown in these figures, the cooperative LMS has similar performance as in the case of average terrestrial conditions.

6 Conclusions

In this short paper, exact analytical expressions for the probability of outage performance of cooperative hybrid terrestrial-LMS have been derived. SR and FR protocols have been examined and evaluated. An accurate simulation framework for the generation of time series for the calculation of the outage probability is also presented. The performance of the cooperative scheme under consideration strongly depends on the shadowing conditions of both the satellite links and the terrestrial one. In most of the cases, the cooperative system offers greater performance than a single satellite system, especially in the case where the terrestrial link suffers from light shadowing. The whole methodology can be also applied to more complex radio cooperative networks, taking into account more relays and more satellite links.

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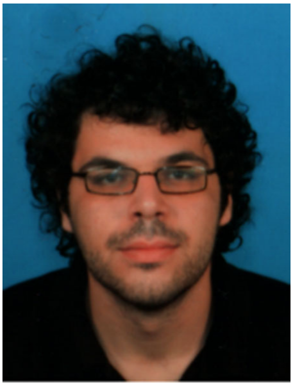

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