Pervasive and Mobile Computing 23 (2015) 139–155

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

journal homepage: www.elsevier.com/locate/pmc

Fast track article

Methodological evaluation of architectural alternatives for an aeronautical delay tolerant network

Rubén Martínez-Vidal [a,*], Ramon Martí [a], Cormac J. Sreenan [b], Joan Borrell [a]

[a] Department of Information and Communications Engineering, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[b] Department of Computer Science, University College Cork, Cork, Ireland

ARTICLE INFO

Article history:
Available online 22 June 2015

Keywords:
Delay tolerant networks
Transoceanic aircraft
Simulation
Graph analysis

ABSTRACT

In this paper, we use graph analysis to evaluate the network architecture of a large scale delay tolerant network (DTN) of transoceanic aircraft. At LCN (Local Computer Networks) 2014 we analyzed information propagation inside a pure opportunistic version of this network, a scenario constructed from more than 2,500 traces of transatlantic flights in which communications relied only on the sporadic contacts between airplanes. As only a small percentage of the nodes were capable of performing efficient air-to-ground communications we concluded the need to devise a more suitable network architecture by combining opportunistic and satellite communication systems. We propose a generic methodology based on graph analysis (both static and dynamic temporal) to evaluate the different ways to create this new architecture. We show the architectural combination that most improves the network delivery performance while minimizing its deployment costs.

1. Introduction

Data communication in aeronautical scenarios is very limited [1]. Airplanes periodically send to ground stations their identification and position, and some company data (few tens of bytes per second). Any other control information is sent over traditional voice-based radio links. These limitations in data communication become more evident when looking for the causes of aerial accidents, as in the case of the ill-fated MH370's disappearance [2].

Regarding passenger data communication, some companies have deployed, for domestic flights, solutions based on external antennas directed to ground [3]. As to transoceanic flights, very few companies choose to use expensive satellite links [4,5] while, in most of the cases, passengers must remain disconnected for hours. On the other hand, most of the research papers on aeronautic transoceanic communications propose the use of communication systems with large coverage (from 300 to 600 km) and thus consider airplanes connected to form an Aeronautical Ad-hoc Network (AANET) [6,7,1].

Looking for a cheaper solution than those based on radio links with high coverage or satellite links, we proposed in LCN (Local Computer Networks) 2013 [8] a new approach based on aircraft equipped with IEEE802.11b/g communication links of only 50 km. This limited range led to a network with a reduced node degree, fully in line with the characteristics of Delay Tolerant Networks (DTNs) [9,10]. To build our network, instead of using synthetic data, we used the actual traces of 2550 transatlantic flights to produce a characterization of a large-scale real-world aeronautical DTN. We analyzed the distributions of active nodes, node degree, number of clusters, any contact time (ACT), and inter-any-contact time (IACT) of that network.

---

[*] Corresponding author.
E-mail addresses: rmartinez@deic.uab.cat (R. Martínez-Vidal), rmarti@deic.uab.cat (R. Martí), cjs@cs.ucc.ie (C.J. Sreenan), jborrell@deic.uab.cat (J. Borrell).

http://dx.doi.org/10.1016/j.pmcj.2015.06.012
1574-1192/

In LCN 2014 [11] we analyzed how data propagate inside our previous transoceanic aircraft delay tolerant network, in order to evaluate the feasibility of using this network as a reliable way to deliver on-flight generated data (either from passengers or company) to the ground. First, we provided an evaluation of two different routing protocols for this scenario: A basic routing protocol using an epidemic dissemination approach, and a version of the protocol which uses a decision function based on an Expected Landing Time (ELT) metric to reduce the data overhead. Then, we showed how only a small percentage of the nodes of the network (7%) was capable of performing efficient air-to-ground communications, by delivering on-flight generated data to the ground at least 5000 s before the landing of the source aircraft, i.e. at least before one third of the average time in which airplanes are disconnected.

Our final conclusion in [11] was that the architecture of our network had to be improved in order to increase the percentage of nodes capable of performing successful air-to-ground communications. To this end, we planned as a future work to devise a more suitable network architecture by combining nodes with just opportunistic communications with nodes equipped with default aircraft satellite communications.

The main objective of this paper, as an extension of [11], is to evaluate the different ways to create this new architecture in order to find the combination that improves the network performance while minimizing its deployment costs. We conduct this evaluation through the analysis of the graph representation of the network. Graph analysis is an established methodology applied to social networks that has been recently used as a powerful and general tool to forward data in DTNs [12–14]. We consider several centrality graph metrics [15], such as degree or betweenness, to determine the smallest possible set of nodes to be equipped with satellite links. Not only static graph analysis is used but also dynamic temporal analysis [16] to achieve a further reduction of the set of nodes and thus of the deployment costs.

Our contributions are as follows:

- We propose a novel ad-hoc network architecture for the aeronautical network scenario we defined in earlier papers, by combining opportunistic and satellite communication systems.
- We propose a generic methodology based on graph analysis techniques and centrality metrics to choose which nodes of the scenario have to be equipped with satellite communication systems. This graph analysis allows us to conduct a complete evaluation of the architecture's performance for use in air-to-ground communications using a custom delay metric (*delivery time reduction*).
- We empirically determine the most efficient centrality metric (*betweenness*) and the optimal parameters that maximize performance while minimizing deployment costs. Finally we show how a dynamic temporal analysis of the associated graph allows further reduction of those costs.

The rest of the paper is organized as follows. Section 2 presents the background and previous work on Aeronautical Ad-hoc Networks, on performance evaluation of DTN over realistic scenarios, and on the use of graph analysis on such networks. In Sections 3 and 4 we provide a comprehensive description of our previous papers [8,11]. In Section 5 we present the new architecture, the two types of nodes which compose it, and the characteristics of the new scenario. In Section 6 we construct the associated contact graph to our network and we analyze it to infer which nodes are the most suitable to be equipped with satellite links, according to several graph metrics. In Section 7 we further refine our analysis taking into account temporal restrictions of the dynamic graph. In Section 8 we discuss our results regarding the costs of deployment. Finally, in Section 9 we present the overall conclusions of the paper and our intended future work.

2. Related work

In this section we review the previous work in design of routing protocols in AANETs, performance evaluation of Delay Tolerant Networks under realistic scenarios, and graph analysis of such networks.

AANETs have the distinguishing feature that they are composed by nodes moving at high speeds that results in highly dynamic network topologies. This has a great impact on the performance of routing protocols, and as a result, providing reliable communications in such environments is a great challenge. Most papers agree with the necessity of a multi-hop based approach for the successful delivery of data within the network. It is also commonly remarked the inability of common Mobile Ad-hoc Networks (MANETs) routing protocols to efficiently deliver data packets when used in AANET environments. There have been a few studies on the field of routing in aeronautical networks, each one presenting their own efficient way to select the optimal route.

One of such studies is the geolocation based routing protocol AeroRP [17]. This routing protocol takes decisions based on a TTI (Time To Intercept) metric which gives an estimation of how soon a neighbor node will be within transmission range of the destination. Some studies regarding this routing protocol offer a performance evaluation [18–20] under different traffic conditions and compare it against common MANET routing protocols.

Another example of such a protocol is DASR (Delay Aware Routing Protocol) [21], a reactive routing protocol which takes decisions based on a expected node delay metric. The authors use performance metrics related to traffic demand and network stability to compare their approach against other routing protocols. Lastly, it is worth to mention MUDOR (Multipath Doppler Routing Protocol) [22], a reactive routing protocol which uses a decision function based on the relative speed of nodes. This protocol aims to select stable paths within the network, and to guarantee links with a long enough duration to successfully forward data.