Satellites, UAVs, Vehicles and Sensors for an Integrated Delay Tolerant Ad Hoc Network

Manlio Bacco[1,3](✉), Luca Caviglione[2], and Alberto Gotta[1]

[1] Information Science and Technologies Institute (ISTI),
National Research Council of Italy (CNR), Pisa, Italy
felice.bacco@unisi.it, alberto.gotta@isti.cnr.it
[2] Institute of Intelligent Systems for Automation (ISSIA),
National Research Council of Italy (CNR), Genova, Italy
luca.caviglione@ge.issia.cnr.it
[3] Department of Information Engineering and Mathematic Science,
University of Siena, Siena, Italy

Abstract. In this paper, a fully meshed mobile ad hoc network is introduced as an alternative to a classical wide area network, as the Internet. Internet of Things, Internet of Vehicles, Unmanned Aerial Vehicles and satellites are the enabling technologies of such a complex scenario with support to multilevel mobility, overlaid deployments, as well as techniques offering Delay Tolerant Networks services.

In this perspective, the paper provides an insight of the most relevant technological issues to guarantee a proper Quality of Service level between an Unmanned Aerial Vehicle communicating with a remote data center through a satellite link. Besides, this work also evaluates the coverage of such a concept in a metropolitan area.

Keywords: Satellite · UAV · IoT · IoV · DTN

1 Introduction

By offering a vast set of services and informative contents, Internet is the worldwide public computer network representing the main medium for mass communication. In the last few years, desktops have been progressively replaced by mobile devices, like smartphones and tables. This trend culminates in many small embedded devices rapidly increasing their presence in the Internet. To this aim, the main technological enabler is the recent evolution of protocol stacks like the IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) [1], which enables to expose a single-tiny device as a node of the Internet. Potentially, 7 billion of users will lead to 10 billions of connected devices: such a vision is commonly called the Internet of Things (IoT).

Another important component is given by ad-hoc networks allowing a device using a wireless link to reduce its utilization of costly data plans to access the

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Internet. The latter are usually too expensive (or not required) compared to the amount of data to be delivered.

While the state-of-the-art literature on ad-hoc networks spans over almost two decades, still, no actual applications use them, primarily due to the poor support of real-time requirements. However, owing to the ferment around the IoT paradigm, jointly with the proliferation of smart and mobile devices, the market for ad-hoc products is becoming relevant. Another important input for the adoption of ad-hoc mechanism is given by the lack of cost-reduction of using wireless accesses offered by Internet Service Providers (ISPs) or Telcos. Thus, implementations of frameworks based on ad-hoc principles are becoming commercially available (see, e.g., [3,4]). Especially, the actual IoT panorama is populated by several monitoring applications to create large data-sets (commonly defined as Big Data) used to elaborate new business or relation models.

Therefore, developing an alternative "internet" to assure a proper internetwork is a convenient solution to avoid grounding on the Internet. We like to name such a deployment *Alternet*. However, connectivity is not the only requirement to be satisfied. In fact, when in presence of high delays and unattended ad-hoc installations, a proper protocol architecture must be available, also to achieve large-scale coverages. Thus, the Delay Tolerant Network (DTN) framework is the preferred solutions to satisfy these constraints.

In this perspective, this paper deals with the characterization of a DTN-based application used in the context of environmental monitoring for smart cities [5]. The key technological challenge consists in building a mobile ad-hoc environmental monitoring network, interconnected by opportunistic links created between public urban vehicles and Unmanned Aerial Vehicles (UAV), i.e., drones. Moreover, a satellite link enables the drone to exchange data towards the remote data center. Performance metrics have been obtained through on-field experiments with a real UAV built by the Information Science and Technologies Institute (ISTI) of the National Research Council of Italy (CNR) [6]. Nevertheless, to understand whether an UAV can be actually deployed in real urban scenarios, simulations characterizing an urban area (i.e., Pisa) are also provided.

The main contribution of this paper is the evaluation of mechanisms to provide a proper degree of reliability when exchanging data, despite the delays or phenomena of intermittent connectivity.

The remainder of the paper is structured as follows: Sect. 2 provides an overview of the reference scenario, while Sect. 3 discusses the setup of simulations. Section 4 showcases numerical results, and Sect. 5 concludes the paper.

2 Reference Scenario

The scenario considered in this work for Alternet consists in a set of "islands" of mobile and fixed ground nodes, such as public vehicles and hotspots. Nodes are not always connected, since are spread in the urban area. Yet, they can communicate when in proximity, as a consequence of their mobility. This usually happens at periodic inter-meeting times between mobile-mobile and mobile-fixed nodes.

The positions of mobile nodes are not known a-priori. Moreover, their routes could never collide, leading to nodes (vehicles) isolated from the rest of the network. As a consequence, some entities will never be able to send data to the remote sink (i.e., the data center). To solve this issue, we use an UAV, which can connect both mobile and fixed nodes with the remote sink.

Due to the scenario, the flying path of the UAV must be large enough to offer the maximum probability of encountering as many nodes as possibles, despite their positions. Then, the UAV periodically returns to the headquarter, where a satellite access point provides a reliable backbone to the dedicated data collection service. Obviously, this methodology can be straightforwardly extended for the case of multiple UAVs.

As regards the method to provide connectivity (with the acceptation of data routability) among fixed, ground mobile and aerial vehicles, a pure epidemic routing protocol [8] is assumed available. Besides, each node composing the architecture is equipped with short-range and high-bandwidth air interfaces. From the physical layer viewpoint, the network is assumed to be mostly disconnected, thus only intermittent short-range links are available.

Figure 1 depicts the map of the city of Pisa, as well as the geographical locations of fixed nodes, the sink and the paths of mobile nodes. Two different paths for the UAVs flights are considered, as to evaluate different metrics, such as the packet delivery ratio, the delays, and the hop count. In our scenario, a very low data rate is supposed to be produced by a sensor source. In fact, according to the aim of the project [5], a telemetry of pollutant and climatic factors is collected firstly to provide a daily and georeferred bulletin. Secondly, another objective is to populate a historical data base to correlate these values with the incidence of cardiovascular pathologies on citizens.

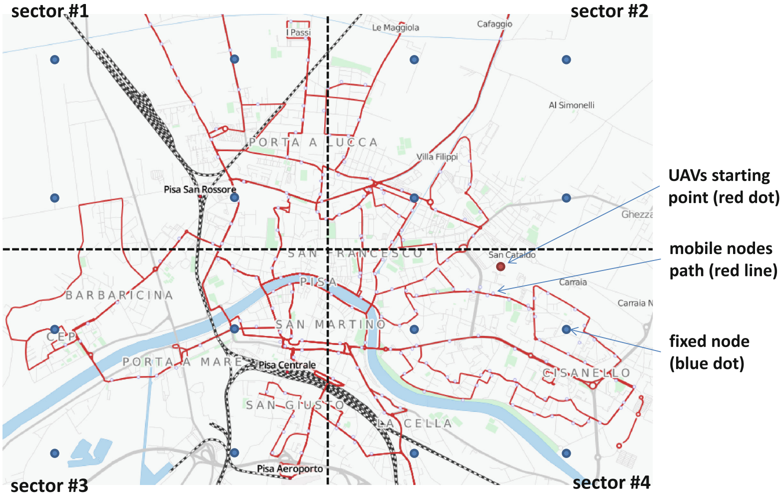

Fig. 1. The map of Pisa used as a reference scenario.

According to the nature of the monitored data, each fixed or mobile sensor node (except the UAVs) generates a 100 byte Protocol Data Unit (PDU) every 5 min. The packets lifetime is equal to one hour and maximum two retransmission are allowed.

Lastly, Fig. 2 portraits the UAV used in our preliminary round of tests used to properly set up the simulator.

Fig. 2. The UAV used in our preliminary round of tests.

3 Simulation Setup

In order to evaluate the Alternet-based architecture proposed in this work, a thorough simulation campaign has been performed. To this aim, a map of $4000 \times 4000\,\mathrm{m}^2$ is considered (built on the topography of Pisa, as depicted in Fig. 1), where fixed nodes are deployed with a regular placement, and mobile nodes can move along predefined routes. The physical space is ideally divided in four equal sectors and four UAVs are used, each of them covering a sector, therefore they can never encounter another UAV while in flight. The UAVs have their recharge base station (the red dot in Fig. 1) where a satellite relaunch is present and devoted to deliver the buffered data from the UAVs to the remote data center. The flight duration is around 15 min, which corresponds to the mean battery lifetime; thus, every 15 min the UAVs leave the base and start their flight in the designed sector after a battery replacement.

In such a scenario, we consider *four* different possibilities to exchange PDUs:

1. a mobile node encounters another mobile node;
2. a mobile node encounters a fixed node;
3. a UAV encounters a mobile node;
4. a UAV encounters a fixed node.

Since an epidemic routing protocol is assumed, when a node encounters another node in its path, it transmits all the packets in the buffer, even if the other node is not the final destination. In this way, the data propagate through the network trying to reach the final target through multiple and different paths. To avoid the saturation both of network resources and buffers, if the data successfully reaches the sink (i.e., the final destination), an *antipacket* is transmitted back to the source node.

In essence, the antipacket is a sort of "receipt" to the source node (see, e.g., the VACCINE mechanism [9]), which triggers the deletion of the acknowledged data from the buffers. Hence, each PDU has a proper `ID`. Additionally, the antipacket gives the "immunity" to nodes, as to prevent the uncontrolled propagation of unneeded data. An antipacket lifetime is equal to the residual lifetime of the packet with the same `ID`.

More copies of a PDU with a given `ID` can reach the sink. In this sense, a routing protocol based on epidemic data dissemination might not be the best choice. However, at this stage, its adoption offers three main advantages: (*i*) its implementation is simple and does not require additional overheads for path discovery or for exchanging Global Positioning System (GPS) coordinates (as it happens in geographic routing); (*ii*) since our scenario implements a totally meshed network exchanging tiny PDUs with a low generation rate, even in presence of duplicates, saturation is an unlikely event; (*iii*) data loss is very low because of the high redundancy.

Regarding the parameters characterising our simulated environment, they have been collected in a preliminary set of trials performed with an UAV in the Pisa Research Area of the CNR. Specifically, equipping nodes with an IEEE 802.11g air interface leads to a range of ∼130 m, as presented in [10] and as confirmed by the measurement campaigns performed with our UAV in the CNR research campus.

The maximum speed for UAVs is 8 m/s. They are equipped with a GPS navigator and can be remotely controlled in a range of 2 km or programmed to follow a GPS route. Since the second modality is more appealing because does not require any human interaction, we did test by implementing two different autonomous flight strategies:

- **random walk**: the UAV randomly deviates from its route, allowing to have a more vast coverage of the sensing area during the flight period;
- **planned way-points**: the UAV follows the fixed routes of ground vehicles (e.g., streets). In this case, PDUs generated by mobile nodes typically have to cross an additional hop toward a fixed node before reaching the UAV.

The proposed scenario has been simulated by using ns-3 [7] and the DTN protocol implementation for ns-3 in [2].

4 Numerical Results

Six different scenarios have been used during the simulations, slightly different with regards to mobile nodes paths, to ensure enough randomness in the movement, as well as the coverage of the whole city area.

Figure 3 shows data and control traffic of one of the simulations. The antipackets are sent back from the remote data center at the arrival of the data packets, and it is visible that they are periodically generated, with a period equal to the flight time of the UAV. The epidemic routing protocol is responsible for the large number of packets in the network, even with a low data rate.

Figure 4 shows the goodput for the six scenarios: the planned UAV flight ensures an higher delivery ratio (goodput) than the random walk, close to 0.9, even if the difference between those is very low, about 0.05.

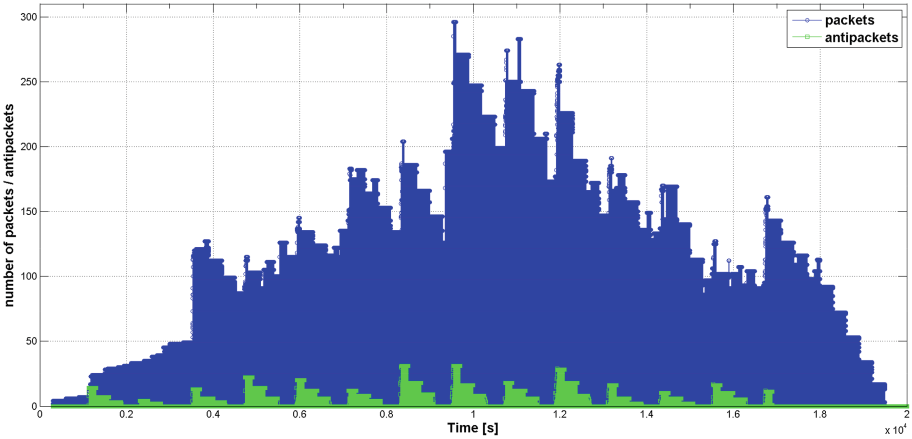

Fig. 3. Data and control traffic during a sample simulation

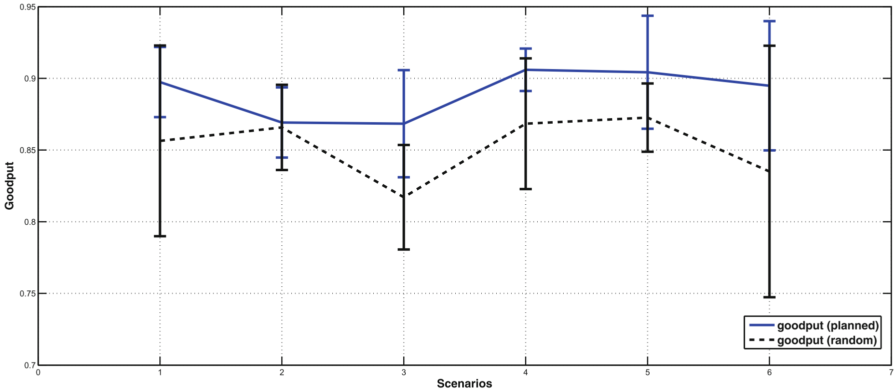

Fig. 4. Goodput of the considered scenarios

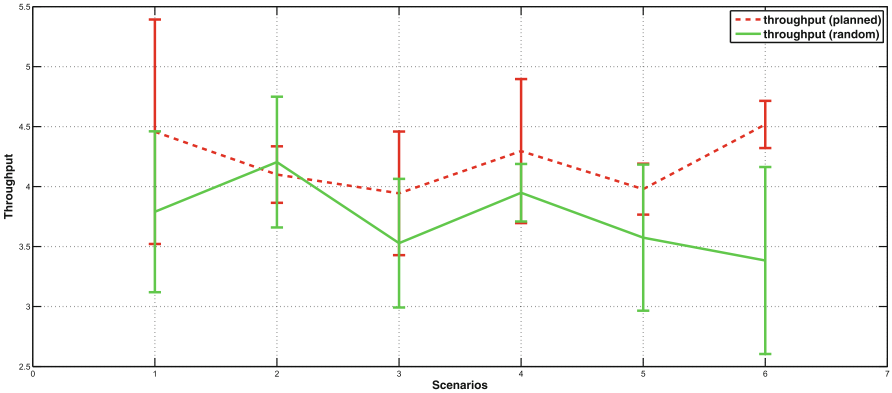

Fig. 5. Throughput of the considered scenarios

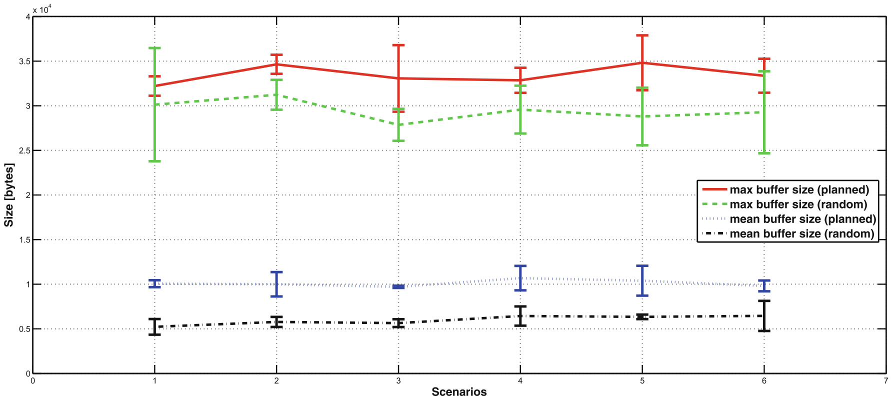

Fig. 6. Buffers Size of the considered scenarios

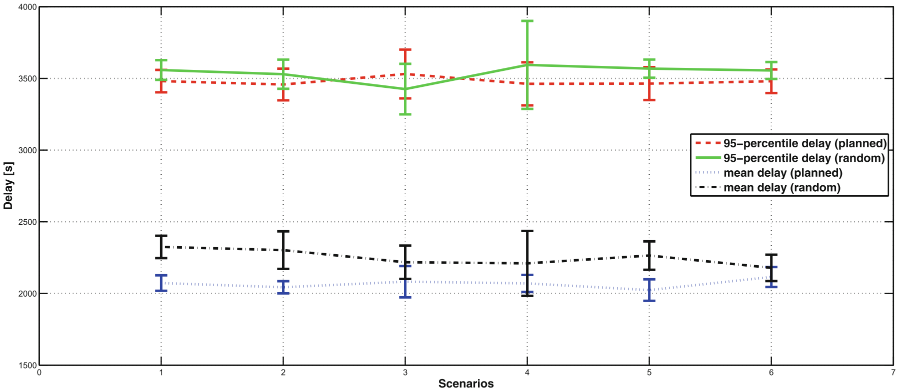

Fig. 7. Delivery Delay of the considered scenarios

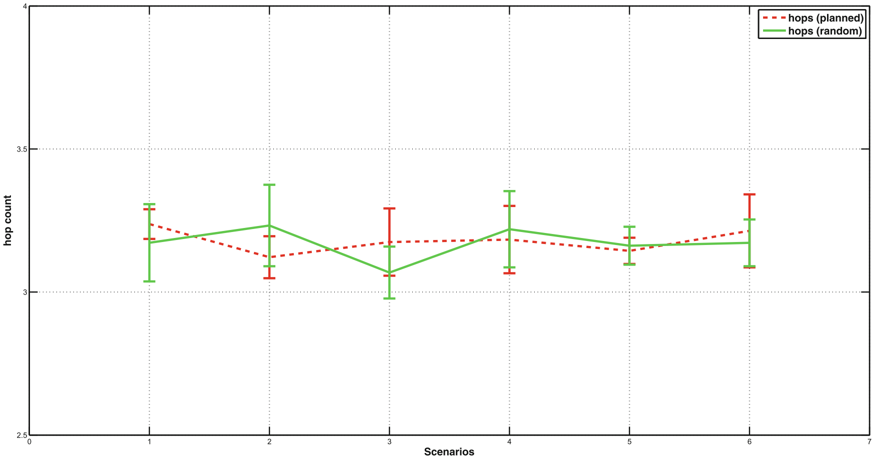

Fig. 8. Mean Hop Count of the considered scenarios

Each scenario shows an high number of duplicates reaching the sink. In fact, the throughput is from fourfold to fivefold higher of the goodput, as showed in Fig. 5. This can be explained by describing the mobile nodes behavior: a mobile node can encounter a certain number of fixed nodes and more than one UAV, because the path may be spread on more than one city sector. The epidemic routing protocol will continuously create packet duplicates, thus increasing the throughput to such an high value.

Figure 6 shows the buffer size of the nodes in the network: it is clearly visible that the planned UAV flight requires larger buffers with respect to the random flight. It is evident that, in the planned flight, an UAV will surely encounter, at least, the four fixed nodes in its sector plus a certain number of mobile nodes; in the random flight, the number of encountering events may be slightly inferior due to the randomness of paths, thus requiring less space in the buffers of the peers.

Figure 7 shows the mean delivery delay and the 95-percentile delivery delay of packets: the random flight has an higher delay, comparing to the planned flight. In the latter case, a greater number of packets is collected during each flight, as confirmed by the buffers size. Then, a higher number of packets is delivered to the sink at each flight with respect to the former case.

In Fig. 8 the mean hop count is shown: the hop count results almost the same for the planned and the random UAV flight, that is ≈ 3.2.

5 Conclusions

In this paper we presented a mobile ad-hoc network-based scenarios using UAVs to collect data produced by ground nodes, to be transferred via a remote sink through a satellite link. The results of the experiments are based on realistic parameters, such as the bus fleet routes in Pisa, the real flight time of a drone, and the wireless communication ranges of vehicular devices. As discussed, we showed the feasibility of providing the communication with a remote data center, with a proper degree of reliability. Also, the analysis of the results provides a metric to design a production-quality monitoring network in a smart city as Pisa, which is a candidate pilot in Italy.

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