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Extending the coverage of the internet of things with low-cost nanosatellite networks

Vicente Almonacid [a,*], Laurent Franck [b]

[a] CSU-IES, University of Montpellier, 860 rue de St Priest, Montpellier, France
[b] IMT Atlantique, 10 Avenue Edouard Belin, Toulouse, France

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ABSTRACT

Recent technology advances have made CubeSats not only an affordable means of access to space, but also promising platforms to develop a new variety of space applications. In this paper, we explore the idea of using nanosatellites as access points to provide extended coverage to the Internet of Things (IoT) and Machine-to-Machine (M2M) communications. This study is mainly motivated by two facts: on the one hand, it is already obvious that the number of machine-type devices deployed globally will experiment an exponential growth over the forthcoming years. This trend is pushed by the available terrestrial cellular infrastructure, which allows adding support for M2M connectivity at marginal costs. On the other hand, the same growth is not observed in remote areas that must rely on space-based connectivity. In such environments, the demand for M2M communications is potentially large, yet it is challenged by the lack of cost-effective service providers. The traffic characteristics of typical M2M applications translate into the requirement for an extremely low cost per transmitted message. Under these strong economical constraints, we expect that nanosatellites in the low Earth orbit will play a fundamental role in overcoming what we may call the *IoT digital divide*. The objective of this paper is therefore to provide a general analysis of a nanosatellite-based, global IoT/M2M network. We put emphasis in the engineering challenges faced in designing the Earth-to-Space communication link, where the adoption of an efficient multiple-access scheme is paramount for ensuring connectivity to a large number of terminal nodes. In particular, the trade-offs energy efficiency–access delay and energy efficiency–throughput are discussed, and a novel access approach suitable for delay-tolerant applications is proposed. Thus, by keeping a system-level standpoint, we identify key issues and discuss perspectives towards energy efficient and cost-effective solutions.

1. Introduction

Recent forecasts indicate that by 2020 the number of connected wireless devices is expected to be near 50 billion [1], following an exponential growth that will be maintained beyond 2030. More interestingly, this trend will not be dominated by personal or hand-held devices but instead by sensor nodes or other *communicating objects*. These are typically small, low-cost, low-power terminals which we generally refer to as machine-type devices (MTDs). It is important to note that the notion of IoT comprises a wide variety of applications. From a communications engineering standpoint, this heterogeneity translates into highly different service requirements in terms of data traffic, end-to-end communication delay, reliability, etc. There are, however, some common characteristics that are present in many applications. In particular, a typical M2M network would be composed by a large number of MTDs generating very short messages with low duty-cycles (i.e., the idle time between consecutive transmissions is high). As we will see later, these characteristics have important implications in terms of energy-efficiency (EE), an aspect of paramount importance in current and future IoT/M2M system engineering.

Currently, there are a number of space-based communications service providers offering global coverage and giving support for M2M-like data traffic. Among these, we may cite well-known systems like Orbcomm, Inmarsat and ARGOS (though the latter is reserved for environmental scientific research). Whereas some of these systems have actually been operating at least since the mid-nineties, their exploitation has not evolved significantly in the recent years (when compared to their terrestrial counterparts). The reasons behind this may be strongly related to scalability limitations and the economic constraints which are inherent to space systems. Thus, there are a number of challenges to deal with in order to provide efficient satellite connectivity for MTDs. For instance, as message sizes become shorter, any type of

* Corresponding author.
E-mail addresses: almonacid@ies.univ-montp2.fr (V. Almonacid), laurent.franck@imt-atlantique.fr (L. Franck).

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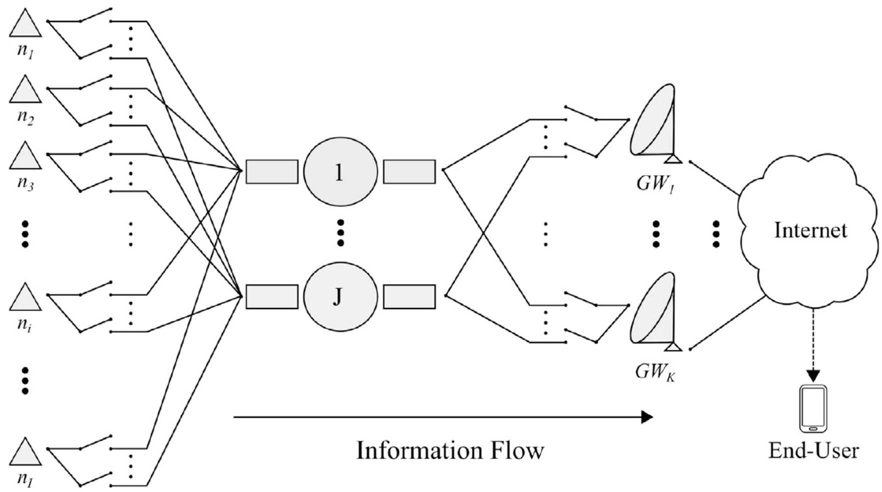

Fig. 1. Network topology.

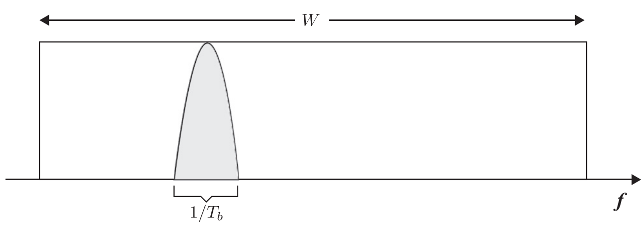

Fig. 2. Available bandwidth and information rate.

communication overhead becomes, in turn, more significant. Additionally, a large number of MTDs connected to a single access point (i.e., the satellite) brings with it the throughput penalties that are associated to multi-user communications.

It is therefore reasonable to imagine that tiny satellites as CubeSats may play an important role in providing extended, low-cost coverage for the IoT. Indeed, while traditional little LEOs (whose mass is typically below 50 [kg]) have a construction and deployment cost that can reach several tens of millions of USD, this cost can be reduced to less than 1M USD for a highly capable 3U[1] CubeSat. From these form factors, it is currently possible to include accurate attitude determination and control systems (ADCS), together with efficient, deployable solar panels. As a result, the range of mission possibilities that we can currently envision is becoming increasingly larger.

As mentioned, the IoT encompasses a large family of applications. In many situations, however, getting just a few bytes of information from MTDs in remote locations—sometimes under extreme environmental conditions—may be highly valuable. Also, in many cases there is no need for low-latency or real-time communications. Systems that are specially designed and optimized to support this kind of applications are usually referred to as *Delay* or *Disruption Tolerant Networks* (DTN) and they represent well the class of services that concern us here.

As a potential application area, we may mention the global network of cargo ships. According to [2], in 2007 there were near 500 000 non-stop journeys of cargo ships bigger than 10000 [GT]. This means that there is an enormous amount of *things* being transported over poorly connected areas during long periods of time (e.g., a typical transatlantic journey takes more than a week). In this context, the end-users are interested in getting information about the state of their goods during transportation. When the number of objects is large, the adoption of a traditional satellite communication link might be prohibitively expensive. Hence, a low-cost solution for providing connectivity for short, daily reports from high value or sensitive cargo may be of great interest for this industry.

Another interesting application area is related to climate change research, which has now become a subject of general concern. In this context, measurement data is usually obtained from sensors located in regions of difficult access, which imposes the use of small, light-weight terminals that might be easily deployed. Here, an appropriate communication solution must be oriented towards simplicity, robustness and EE.

While a general study on the use of satellite systems to provide global IoT/M2M connectivity has been recently presented in Ref. [3], the idea of using CubeSat platforms has not been studied in other research publications, to the authors knowledge. Our aim here is thus to introduce and discuss this idea, focusing on some of the fundamental issues related to communications engineering. The paper is organized as follows. In Section 2, we present a general model of the IoT/M2M network envisaged. Then, in Section 3, we revisit link design concepts in order to show how the system constraints impact the uplink capacity. Issues regarding EE are discussed in Section 4. Taking into account the discussions in the previous sections, the design of an appropriate access scheme is treated in Section 5, where the notion of delay-tolerant multiple access is introduced. Finally, Section 6 concludes this work.

2. System modeling

The model we present next is intended to provide a general description for the type of IoT/M2M network of interest. The system is composed by I MTDs, J satellites in LEO and K Earth stations or gateways (see Fig. 1). We assume that the only sources of data traffic are the MTDs. MTDs may be located anywhere in the world, though they are more likely to be installed in remote, non-urban areas. When a MTD has packets to transmit, it waits until any of the J satellites is visible and then transmits its packets on the uplink, following an *opportunistic* channel access scheme (see Section 3.1). The satellite visibility at a given location on earth is limited to a time interval T_w that we call the *visibility window*, and we define it as the time-window over which the satellite is seen with an elevation angle ε that is above some threshold ε_{min}. Packets that are successfully transmitted on the uplink are stored in a buffer and then forwarded to the first gateway visited by the satellite. At this point, we assume that the information can be immediately retrieved by the end-users, given that the gateways are connected to the Internet. Due to size limitations, a MTD can only be equipped with an omnidirectional antenna. Similarly, it is hard to implement high-gain antennas on-board the satellites, specially if the system operates over low radio frequency

[1] Standard CubeSats are build upon cubic units of approximately $10 \times 10 \times 10$ [cm^3], corresponding to the 1U form factor.