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Low-Power IoT Networks for Space Applications



Abstract: - The volume of traffic produced by Machine-type Communications (MTC) is increasing rapidly, exerting significant strain on current network infrastructures. One of the most formidable issues nowadays is facilitating machine-to-machine (M2M)/Internet of Things (IoT) data exchanges by ensuring connection between any two M2M devices globally. Consequently, this study examines the function of Space Information Networks (SINs) in facilitating MTC.

This document examines horizontal solutions to facilitate interworking by serving as relay entities across various protocol stacks and services delivered vertically across distinct network segments. We examine the unresolved problems obstructing interworking and offer a potential protocol stack for M2M/IoT communications based on the oneM2M standard. This research ultimately evaluates the performance attainable via two widely used application protocols, Constrained Application Protocol (CoAP) and Message Queuing Telemetry Transport (MQTT), elucidating their efficiency and distinctions.

Index Terms: Internet of Things, Machine-to-Machine, CoAP, MQTT, performance evaluation, openM2M, openMTC

INTRODUCTION

SPACE Information Networks are intricate network infrastructures that depend on various interconnected segments, established by space platforms such as satellites, Unmanned Aerial Vehicles (UAVs), High Altitude Platforms (HAPs), and airships, which facilitate data acquisition and processing across numerous application domains. SINs offer global coverage, thereby serving a crucial function in various applications: connectivity for remote regions, emergency communications, environmental monitoring, Massive Machine-type Communications (mMTC), and interplanetary communications, among others. The network segments of a SIN exhibit distinct needs and features, necessitating interworking as a primary purpose.

The latest advancements in tiny satellite technologies are rendering the use of small satellite-based systems attractive for several applications, including IoT. A practical example is the DSAT project [3], which involves a flexible Cubesat-based system designed and tested to transmit data generated by Manlio Bacco, Pietro Cassarà, Marco Colucci, and Alberto Gotta from the Institute of Information Science and Technologies (ISTI), CNR, Pisa. Luca Boero, Mario Marchese, and Fabio Patrone are affiliated with the University of Genoa, Italy. Their email addresses are luca.boero@edu.unige.it, mario.marchese@unige.it, and f.patrone@edu.unige.it.

sensors distributed throughout a specified coverage region. Currently, establishing communication between any two M2M devices globally is one of the most formidable challenges. This intrinsically multidimensional topic is examined in this paper from two distinct perspectives: network connection and interoperability for services and applications.

As outlined in [1] and [2], the first difficulty of network connection must be addressed by establishing a backbone capable of facilitating data flow (i) between ground stations and (ii) between space platforms and ground stations, ensuring minimum latency in both instances. The primary aim is to expand the observation scope about the capabilities of an individual network segment, such as a solitary satellite component. Seamlessly integrating disparate network segments may be problematic, as can delivering applications and services that are usually implemented as vertical solutions atop individual network segments. Earth observation, Internet connection, satellite-based cellular connectivity, environmental monitoring, and wide area measurement systems are instances of services that often use a single network segment in almost all implementations. The IoT ecosystem exemplifies fragmentation by the lack of a universally accepted standard for MTC; a widely embraced horizontal architectural solution that facilitates interoperability across diverse application stacks, hardware, and services is absent. As expected, a complex problem must be addressed to progress towards a cohesive network vision that integrates diverse hardware and software components.

Section 2 delineates the network portions of a SIN, while addressing and analyzing the prevailing problems. Section 3 addresses MTC services and applications. We emphasize the growing need for open standards to

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effectively facilitate interoperable MTC scenarios linking far entities, and we suggest a relay method to connect remote M2M/IoT devices inside a SIN-based heterogeneous network.

In Section 4, we conduct a qualitative comparison of the performance levels attainable by two application protocols in SINs, emphasizing their distinct characteristics and potential.

MTC APPLICATIONS AND SERVICES

The next fifth generation of cellular technology will provide an uninterrupted stream of novel services and applications, underpinned by both physical and virtual Radio Access Networks (RAN). The softwarization and virtualization of RANs will be realized using the previously described SDN and NFV concepts. To facilitate extensive IoT internetworking, the synergistic use of aeronautical networks will be essential to manage the substantial volume of traffic, especially in regions that are traditionally unconnected or inadequately serviced. In this situation, SINs may significantly assist in integrating various network parts. Literature and industry studies indicate that M2M/IoT markets remain fragmented, while horizontal solutions, which serve as intermediary organizations to connect various vertical protocol stacks deployed, even privately, across distinct network segments, are rather uncommon. Vertical complete turnkey solutions are often favored, particularly for commercial considerations. Consequently, enhanced integration and interoperability are essential for various networks.

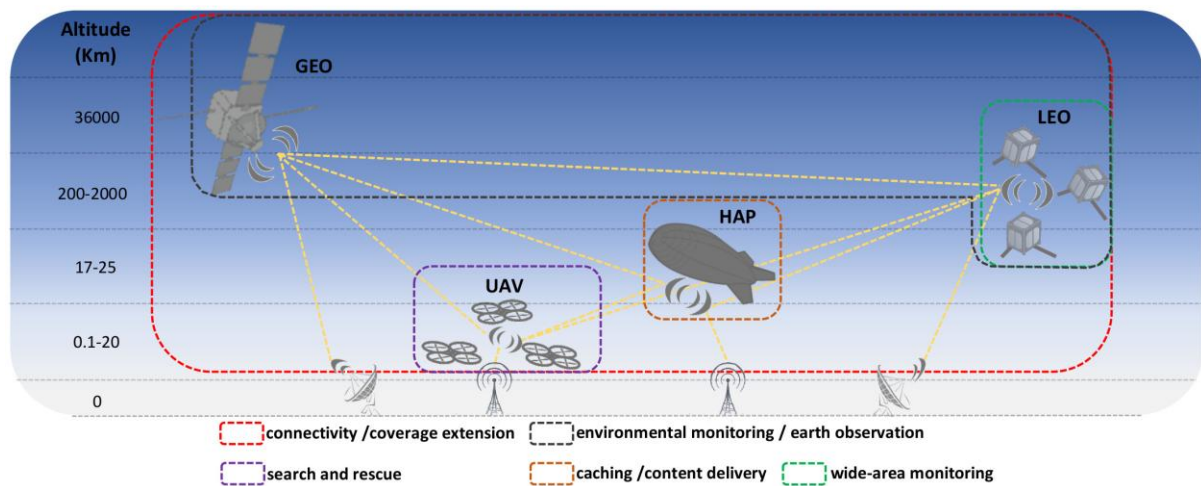


Fig. 1: Network segments composing a SIN at different altitudes.

Illustrations of applications and services are shown, demonstrating the potential interconnections among various network segments and the application scenarios built upon them. An architectural methodology is presented in [4] and implemented in the context of IoT in [12].

As mentioned in Section 1, establishing communication between any pair of MTC devices globally is regarded as one of the most formidable challenges today. The SIN paradigm seeks to provide a comprehensive communication network by integrating various network segments, hence enabling connectivity between any pair of distant endpoints globally. Various facets, including routing, security, and protocol stacks, must be addressed via meticulous research and policy to comply with diverse global needs and legislation.

Conversely, there is a need for an open standard to facilitate the interchange of M2M/IoT data. The poll in [13] outlines the issues posed by the need for interoperability across several levels of the end-to-end protocol stack, identifying this requirement as one of the most critical for the success of the ecosystem. The oneM2M group aims to harmonize M2M standards. It establishes a service layer for the interchange of data between M2M entities in a manner that is independent of the underlying network.

oneM2M formulates technical specifications for a service layer that interconnects a multitude of M2M devices globally in an interoperable manner, catering to the diverse requirements of various business sectors, including smart cities, smart factories, and smart villages. Regarding compatible software implementations of oneM2M, openMTC offers an open-source middleware solution that facilitates the horizontal integration of various devices. Figure 2 illustrates the logical architecture for interconnecting M2M/IoT devices globally; in this context, openMTC serves as a middleware solution facilitating the conversion from non-oneM2M domains to oneM2M-compliant domains inside gateways, hence providing access to distinct network segments. openMTC is

independent of the underlying network, which we presume consists of both terrestrial and satellite networks. In the proposed concept, M2M/IoT nodes may be classified as either resource-rich or resource-constrained devices. The former has a complete TCI/IP protocol stack integrated onboard. In the latter case, the data are sent directly via a data connection or a streamlined network layer.

In both instances, data created or collected by M2M/IoT devices will pertain to a certain domain and be appropriately structured [13]. In the event of resource-constrained devices, an extra gateway (not shown in Figure 2) is required to de-encapsulate the data and then re-encapsulate it inside the TCP/IP stack. Utilizing openMTC gateways enables the transmission or retrieval of data by services and applications after its conversion to a oneM2M-compliant data format. The openMTC gateway may be logically co-located with a Ground Control Station (GCS) that facilitates communication with space network segments, offering horizontal translation services for vertical application domains and ensuring transparent connection across various network segments.

COMPARATIVE ANALYSIS OF COAP AND MQTT IN SENSORS

This section compares the performance of CoAP and MQTT when implemented over synchronous data connection protocols in long-delay Random Access Channels (RACHs), using the performance assessments from references [14] and [15]. The former considers scenarios of medium to high traffic load, while the latter addresses low traffic conditions. This review presents an analysis using goodput as the performance indicator, while also addressing overhead, complexity, and deployment ease.

Figure 3 illustrates the attainable normalized goodput at the application layer, using CoAP and MQTT. The average goodput value for both procedures is shown for normalized loads ranging from 0 to 1. The 0.25 and 0.75 quantiles are shown with the mean values (straight lines), indicating that MQTT exhibits more variability than CoAP around its mean values due to TCP bandwidth probing. To elucidate the implications of the data shown in Figure 3, we will examine low, medium, and high load levels individually, since the application layer experiences varying loss rates under these circumstances. The loss rate is minimal at low loads, allowing for the implementation of simple solutions that provide high energy efficiency and low complexity for dependable exchanges; however, this is not the case for larger loads. Medium load situations are defined as those aligned with the system's operational points when using TFRC-like congestion management algorithms [14]; heavy load conditions are characterized by significant loss rates.

The load shown in Figure 3 is directly correlated with the quantity of devices concurrently broadcasting in a RACH; in this instance, the devices may function as CoAP proxies or MQTT brokers.

CoAP may use the basic congestion management technique inherently offered by its straightforward implementation during periods of low traffic. The simplicity leads to minimal computing demands on available resources, which is essential for resource-constrained devices. Augmenting NSTART, the CoAP parameter that restricts the number of concurrent outstanding contacts clients may sustain with a certain server, results in a roughly linear increase in goodput under low loads, attributable to the minimal contention level. In the context of MQTT, the TCP congestion management algorithm regulates the transmission rate, from which the attainable goodput is derived. In summary, a number for NSTART may be determined that yields equivalent performance between CoAP and MQTT. In [15], the authors experimentally determine this value by establishing $NSTART=5$. Under medium to high loads, the inherent use of NSTART becomes inadequate owing to heightened contention on the RACH, resulting in anticipated performance decrease as the load escalates. Consequently, the implementation of a modified TFRC congestion management method for CoAP, referred to as TFRC-s, in conjunction with a selective-repeat Automatic Repeat reQuest (ARQ) algorithm is proposed in [14]. The suggested approach affects just rendezvous nodes (i.e., CoAP proxies), leaving both publishers and producers unaltered. The implementation of a TFRC-based algorithm enables performance levels that are equivalent to, or even exceed, those achieved with MQTT, due to reduced protocol overhead and the characteristics of TFRC. Ultimately, MQTT offers a readily deployable solution, using the stability of a TCP-based architecture. A greater prevalence in practical applications than CoAP should be noted, attributable in part to its earlier market introduction and its intrinsic provision of a trustworthy solution. Conversely, CoAP is gaining interest in comparison to MQTT. It signifies a more adaptable solution, with optional elements that provide further functionality at the expense of heightened complexity. In other words, it facilitates a gradual approach that is advantageous in a diverse market ecology of M2M/IoT devices with varying needs.

SATELLITE BASED IOT NETWORKS

Typically, satellites and IoT do not seem to be inherent collaborators in the realm of communication. Nevertheless, owing to the exigencies of certain circumstances, they encounter one another on several occasions. Consequently, there are several justifications for integrating IoT with satellites to address these specific requirements. This section delineates the primary causes for their conjugation. Figure 1 illustrates a satellite-based Internet of Things network. The satellite's service region is shown as an ellipse encompassing the IoT network. The IoT transceivers are represented by triangular towers, while the sensor nodes are shown by red dots. Both the Internet of Things and the satellite connections are wireless.

A. Motivation for Satellite IoT Integration

1) Reliability in the wireless applications

The reliability of wireless communications remains a significant challenge. Conventional wireless networks lack the high dependability necessary for mission-critical applications. These concerns may be resolved using satellite networks. Satellites often provide superior dependability compared to cellular networks. With optimal constellation configurations, satellites provide over 99.9% availability, much surpassing contemporary cellular networks. This is vital for mission-critical applications, including disaster management and military communications. High availability guarantees exceptional dependability under many settings.

2) Larger and broader coverage of the IoT Networks

IoT networks are often implemented via the existing cellular infrastructure. The cellular networks are designed based on human presence. Consequently, the coverage of cellular networks is somewhat restricted. For really tall towers, the coverage radius is around 20 kilometers. Tall structures are inappropriate for environmentally friendly applications due to their elevated radiation concentrations. Satellite networks may include extensive regions and do not exhibit bias towards any specific topography. Consequently, for extensive multi-functional implementations, satellite-based IoT systems are favored over cellular IoT systems.

3) Better Security and Protection

SIoT networks are significantly influenced by the presence and availability of satellites. Intercepting and controlling these systems is very unusual and requires substantial effort. In contrast, cellular networks are very deficient in security and isolation. Furthermore, satellite networks have implemented enhanced security protocols, including anti-jamming technologies and robust cryptographic encryption that are not readily compromised.

4) Economical and faster rural deployment:

Economics significantly influences all communication technologies. In the context of IoT, it assumes even more critical functions because to the excessive number of ground terminals and sensors. The rural implementation of any IoT is heavily contingent upon the prevailing economy. SIoT is very promising in this context, since satellites provide broader coverage and satellite-based IoTs need less resources than cellular IoTs. Undoubtedly, the specialized energy-efficient variants of the IoTs will better serve this market. This element of SIoT is discussed later in section IV of this article.

5) Multicasting of services:

Every satellite have a distinct coverage area. These are contingent upon their beam widths. The coverage area of a satellite often exceeds that of cellular transmitters significantly. Consequently, satellite multicasting is much more efficient and economical than cellular broadcasts. The IoT-based multicasting is very advantageous in scenarios with strict energy limitations.

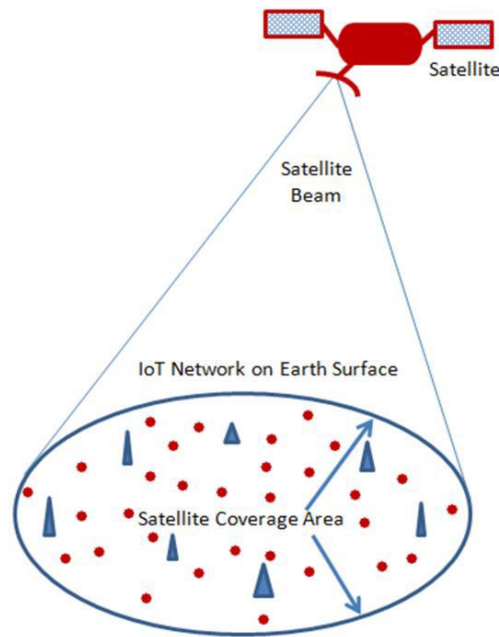


Fig. 2. Satellite based IoT Network.

SUSTAINABILITY OF SATELLITE BASED IOT NETWORKS

The integration of satellite and IoT creates a complex network. Contemporary satellites serve several functions. Consequently, SIoT applications via satellites will only constitute an additional category of satellite applications. The sustainability of the SIoT has two components. One pertains to terrestrial applications, mostly within the IoT sector, while the other relates to the spatial environment around the satellite. Effective coordination between both segments is essential for the long-term viability of SIoT networks. In terms of energy, many kinds of IoTs need transmitters and receivers with distinct requirements. Currently, energy-efficient IoTs are accessible, and ultra-low energy consuming IoTs are gaining popularity. For effective satellite connecting, the received quantities must exceed the threshold values of the IoT receivers.

CONCLUSIONS

This study presents the network infrastructure of SINs, emphasizing the many associated network parts. This intricate software and hardware architecture facilitates global communication, effectively permitting data transfers between any pair of M2M/IoT devices. This article presents examples of application situations that potentially gain from global coverage, along with the unresolved difficulties that need to be addressed. To get towards ubiquitous MTC connection, the establishment of open horizontal standards is essential for ensuring interoperability and transcending vertical solutions. This perspective introduces a potential horizontal relay solution to facilitate M2M/IoT-based application situations. We investigate two widely used application protocols, CoAP and MQTT, comparing their performance levels in scenarios requiring reliable data exchanges across long-delay networks.

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