A Scalable Packet Routing Mechanism for Chip-Satellites in Coplanar Orbits

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This article is motivated by the advent of gram-scale spacecraft, or "chipsats," which enable satellite networks composed of hundreds of thousands of nodes. Networks of this size necessitate routing policies unlike any that have been used for collections of conventional spacecraft. This article argues which information should and should not be assumed available to each node in such a network. Based on these argued assumptions, this article uses dynamic programming to derive a routing mechanism for planar collections of chipsats. It, then, shows that the resulting mechanism is optimal for collections of orbits that are all near enough in altitude to communicate with one another, and also for collections of circular orbits. This article shows that the derived mechanism is suboptimal for collections of nested, unconnected orbits, and for stochastic collections of unconnected orbits. The particular form of the routing mechanism derived in this article is unique to planar collections of orbits, but the structure of the mechanism generalizes to three dimensions.

Manuscript received April 30, 2019; revised September 19, 2019; released for publication February 3, 2020. Date of publication March 2, 2020; date of current version October 9, 2020.

DOI. No. 10.1109/TAES.2020.2977791

Refereeing of this contribution was handled by T. Rossi.

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I. INTRODUCTION

To a greater extent than ever before, the past two decades has seen scalability become a core design consideration for a handful of engineered systems. Cell phones are the best example of such a system. Consumers purchased 1.56 billion smartphones in the year 2018 [1]. Each of these devices, in addition to being optimized for operation as an autonomous machine, was also optimized for cooperation with billions of other such devices. Manufacturing methods, communications protocols, and distribution strategies were all conceived with the understanding that billions of such devices would be built, distributed, and operate in a cooperative manner. This is what scalability means in the modern era, and it is the definition used in this article. A scalable system is one that works efficiently over and among an arbitrary number, perhaps billions, of iterations and constituents.

Defined as such, engineers do not yet optimize for scalability when designing spacecraft and spacecraft systems [2]. The volume of spacecraft built and launched each year is simply too low for scalability to be a reasonable criterion by which to judge potential spacecraft designs [3]. Instead, the relatively small volume of spacecraft (small relative to the volume of other complex engineered systems, like cell phones) generally favors bespoke solutions for each mission. This method has been radically successful, and has brought decades of commercial and scientific activity in space. Because this strategy works, there is no reason to expect for it to go away. There is, however, reason to expect that new strategies will become viable alternatives to this one.

Not long after people started launching spacecraft, they started launching spacecraft constellations. Many of the early satellite constellations facilitated communication. The first test of a space communications relay system was Pioneer 1 in 1958 [4]. In 1964, Syncom 3 and Relay 1 worked in concert to provide television broadcast in the United States of the summer Olympics in Tokyo, marking the first time that two spacecraft cooperated for that purpose [5]. Today, Globalstar, Inc maintains a constellation of 48 satellites for low-speed data communication [6], ORBCOMM has 31 satellites in orbit to facilitate communication [7], and Iridium has 66 [8]. A few other constellations for other purposes have also been launched, most notably the GPS constellation, composed of 24 spacecraft [9] and Planet Lab's Earth imaging constellation of over 140 spacecraft [10]. Even larger constellations are planned for the near future. SpaceXs Starlink constellation will be composed of nearly 12 000 spacecraft [11]. The trend toward scalable spacecraft (scalable in the spirit of cell phones) has been underway for a long time. We can expect for this trend to continue as the economics surrounding building and launching spacecraft continue to change.

The economics surrounding processors, radios, sensors, and printed circuit boards have changed particularly rapidly due largely to technology industries of scale, such as those surrounding cell phones and gaming [12]. The consequence