A Network Architecture for Precision Formation Flying Using the IEEE 802.11 MAC Protocol[1]

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Abstract—Precision Formation Flying missions involve the tracking and maintenance of spacecraft in a desired geometric formation. The strong coupling of spacecraft in formation flying control requires inter-spacecraft communication to exchange information. In this paper, we present a network architecture that supports PFF control, from the initial random deployment phase to the final formation. We show that a suitable MAC layer for the application protocol is IEEE's 802.11 MAC protocol. IEEE 802.11 MAC has two modes of operations: DCF and PCF. We show that DCF is suitable for the initial deployment phase while switching to PCF when the spacecraft are in formation improves jitter and throughput. We also consider the effect of routing on protocol performance and suggest when it is profitable to turn off route discovery to achieve better network performance.

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1. INTRODUCTION

Numerous space missions have been proposed that are composed of multiple spacecraft that are spatially distributed. Distributed spacecraft missions have been classified into general types to serve different purposes, and may require or benefit from inter-spacecraft communications networking. For example, constellations are composed of spacecraft separated by relatively large distances that are generally varying, and might use communications to provide a relay infrastructure for ground users or to rapidly deliver science telemetry from on-board sensors to ground users [1]. In this paper, we focus on the Precision Formation Flying (PFF) distributed spacecraft class, which promises revolutionary advancement enabling large aperture and interferometric imaging capabilities [2].

Precision Formation Flying (PFF) is the collective use of multiple spacecraft to perform the function of a single, large, virtual instrument [3]. For example, two or more telescopes may be used to form an interferometer that has the effective power of single telescope with an aperture much larger than any of the individual elements. The spacing among the multiple spacecraft can range from tens of meters to hundreds of kilometers apart. Tracking and maintenance of spacecraft in a desired geometric formation requires distributed spacecraft to exert collaborative control of their mutual positions and orientations. The strong coupling of spacecraft in controlled formation requires inter-spacecraft communication to exchange information concerning relative and absolute positions and orientation.

Examples of proposed PFF missions are listed below:

- The Terrestrial Planet Finder Mission (TPF) [4], planned for 2015 launch, will detect and study distant planets. TPF is considering two configurations, one of which consists of a large-baseline interferometer operating in the infrared. There will be five spacecraft: four collector telescopes in a line formation (75m – 1km baseline), and a combiner spacecraft at a position offset from the line at a bisector point.

- The Micro Arcsecond X-Ray Imaging Mission (MAXIM) [5] is an X-ray observatory that will use X-Ray interferometry to achieve 100 nanoarcsecond resolution for investigation of black holes. MAXIM is planned for 2017; it entails 33 optics spacecraft in a circular wheel formation where the diameter of the circle is approximately 200 meters. There is one

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Because of the requirement to scale to PFF missions consisting of tens of spacecraft, the system design is driven to consider networking solutions in which the network nodes dynamically share a common communications channel. This avoids the obviously infeasible approach of creating a fixed assignment of $N*(N-1)$ one-way channels (1122 for a 34 spacecraft network) for all possible inter-node communications. Basing the networking on a shared medium also facilitates scalability across PFF missions. In addition, such an architecture naturally accommodates "accretionary formations" [9] where the PFF is built up incrementally over time.

A general system design principle is to maximally leverage available conventional technologies. Space communications standards are maintained by CCSDS [10], which consists of 10 member agencies (including NASA), 22 observer space agencies and over 100 industrial associates worldwide. The CCSDS standards span all protocols layers, and accommodate both deep space and "proximity" communications. However, no CCSDS protocol currently exists that provides dynamic frame-level channel sharing, as heretofore this functionality has not been needed. Recognizing the realtime deterministic delivery requirements of the control application, we might consider emerging wireless networking approaches in the industrial automation environment, such as wireless Profibus [11] or wireless CAN [12]. However, we select the ubiquitous 802.11 MAC standard as it provides sufficient controllability through the use of the Point Coordination Function (PCF) capability to satisfy the PFF networking requirements, while also providing the Distributed Coordination Function (DCF) random access needed when there is limited positional and topological knowledge (during the neighbor discovery upon initial deployment, during formation reconfiguration, and during fault "lost-in-space" conditions). It is emphasized that we do not necessarily use a standard 802.11 physical layer, although we do assume that the physical layer will provide the necessary interface signaling required by the 802.11 MAC standard.

The position sensing system required for the formation control is assumed to be independent of the communications network in the protocol stack design presented in this paper. However, it is likely that both the communications and (at least coarse-grain) position sensing will use Radio Frequency (RF) media, leading to possible system efficiencies by considering integrated designs. For example, the Autonomous Formation Flying (AFF) distributed RF sensor system [13] has a signal structure that is capable of exchanging range and bearing telemetry simultaneously with the sensing waveform (which uses GPS-like pseudo-range code and carrier information). Wang and Zhang [14] describe an integrated system performing round-trip ranging and communications with a spread spectrum system.

Lower layer communications protocols for PFF networking were investigated by Kusza and Paluszek [15], including consideration of X.25/LAP-B/HDLC, ATM, IEEE 802.11 and CCSDS Proximity-1 and CCSDS AOS. A survey of existing and planned inter-satellite link protocols is presented. Regarding use of the 802.11 physical layer, they indicated that "it remains to be determined whether or not IEEE can adequately scale up to the power and range requirements." However, use of the 802.11 MAC was acknowledged to as a possibility. In this paper, we further investigate the use of the 802.11 MAC.

Investigation of inter-satellite networking in general distributed spacecraft missions, including formation flying missions, was treated in [16] (see also [17] listing distributed spacecraft missions). Based on a survey of 39 proposed distributed spacecraft missions, requirements were identified. Protocols that may be considered for use and standardization in this context were presented, specifically identifying 802.11, 802.15/Bluetooth, 802.16, HomeRF, and CCSDS Proximity-1.

Additional studies of communications protocols for PFF networks have been presented in [18-20]. Knoblock et al. [18] and Megla et al. [19] consider the relay of files between PFF spacecraft and ground users, and provide simulation analyses including TCP/IP protocol behavior and the ground network. Comparison of the FTP and SAFE file delivery protocols is given in [18] where either ATM (in a star configuration) or 802.11 is used for communications among the PFF spacecraft. In [19], the intra-PFF network was modeled as either wireless 1394 or 802.11, and two alternative PFF network sizes (7 or 13) were modeled, with traffic generated as FTP file transfers between the spacecraft and the ground. Megla et al. [20] focused the investigation of FTP file transfers within the local PFF spacecraft network, modeling both wireless 1394 and 802.11. These studies presumed a static network in which the spacecraft where in formation; in our work, we emphasize the dynamics the PFF mission as it evolves through phases that pose significantly different communications requirements.

The paper is organized as follows. In Section 2, we discuss elements of the PFF application that impact the networking architecture. Section 3 presents the protocol stack proposed for the PFF missions, incorporating the IEEE 802.11 MAC protocol. The proposed protocol stack includes a new application layer protocol that is described in detail in Section 4. Section 5 provides a performance analysis of IEEE 802.11 MAC in DCF mode operating in the context of a PFF environment with large inter-node distances. Results from simulation experiments are presented in Section 6 that incorporate

which two antennas were combined at RF to achieve nearly isotropic coverage is given in [21]. It is noted that integration of the communications and the position sensing system will require consideration of this shared channel aspect; for example, the AFF [13] is designed with two transmitters and 4 receivers per spacecraft, with associated signal processing for each. This enables such functions as azimuth and elevation bearing determination, and multiple channels will be presented to the communications system.

Spacecraft Communications Capabilities

Each spacecraft is assumed to have the processing capability to implement the protocol stack to be described in the next section. This will enable autonomous operations that are known to be required in PFF missions. We also assume that one spacecraft is designated as the "leader" spacecraft that (1) performs centralized processing of the formation control (at least at the supervisory control level), and therefore plays a special role in terms of the traffic pattern, and (2) plays a central role in the communications networking, including acting as the Point Coordinator when 802.11 PCF mode is in effect, as well as special functions in executing the Application Protocol.

Communications Topology

The PFF spacecraft are assumed to initially be deployed distant from one another, and moving (laterally and rotationally) essentially randomly. During this time, each spacecraft is possibly out of communications with any other. As a spacecraft progresses toward the formation area, it will eventually discover another spacecraft, which may be itself isolated or may be a member of a multi-spacecraft network. When a subnet of greater than two spacecraft is formed, it may consist of a multi-hop topology, requiring routing to pass data throughout the subnet. One of these subnets will contain the leader spacecraft. This situation is depicted in the upper portion of Figure 1. As the spacecraft continue toward the formation, all spacecraft will become members of a single connected network, although a multi-hop topology will be present; this is depicted in the center portion of Figure 1. Finally, when the spacecraft are closer to the desired spatial formation, the topology will have evolved to have an embedded star graph with the leader spacecraft as the star's center. This is shown in the bottom of Figure 1. Note that in this final topology, the connectivity may be greater than a star (such as fully connected); we require only that the star topology is embedded.

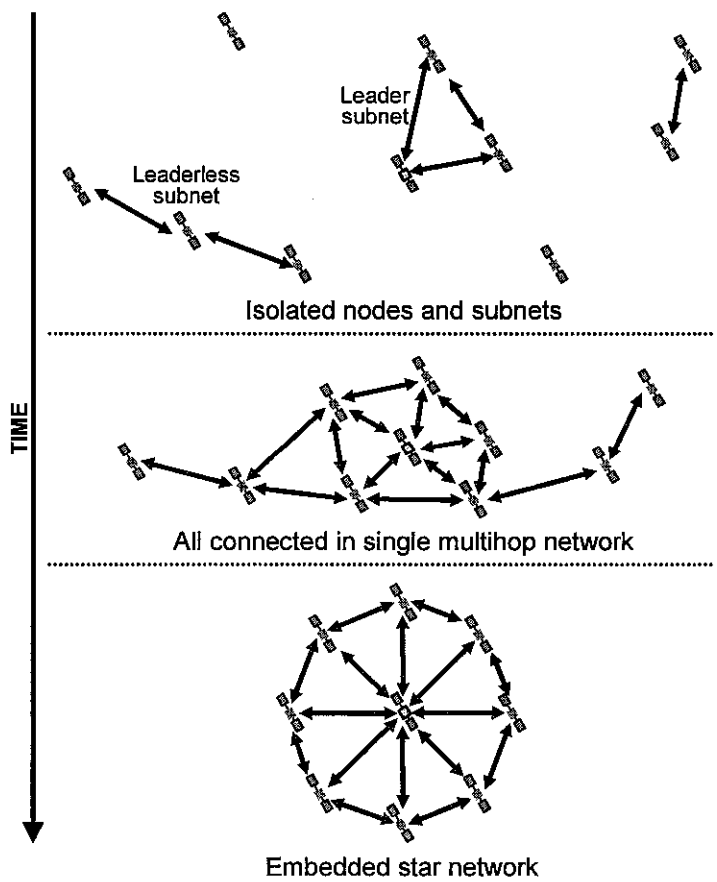

Figure 1. Topologies Corresponding to Evolutionary Phases of a PFF Mission

these periods will be small, so that the load on the network, even using the minimum data rate, will be low. This will ensure that random access frame collisions will be rare, and resolved quickly in the unusual cases where they do arise. PCF mode will be used when the spacecraft are in coarse or precision formation, when the network topology is known to

The broadcast capability of the 802.11 protocol will also be utilized (specifically in the DCF mode). Use of the RTS/CTS protocol enhancement to reduce "hidden terminal" contention when the topology is multi-hop is not likely needed, given the assumption of low offered load during this period. The RTS/CTS should be disabled when the spacecraft are in formation, as it would otherwise degrade performance when it is needed most.

A standard Logical Link Control (LLC) 802.2. sublayer is used. This will provide addressing service to the network layer. Basic unacknowledged connectionless service will be provided to minimize overhead. Standard LLC and MAC sublayer management entities are also assumed. It is possible that the PFF application, which is cognizant of actual spacecraft positions, could interact with the MAC layer to improve communications performance. For example, once it is known that the spacecraft are in formation and using traffic to/from the leader via PCF, the RTS/CTS function could be turned off (assuming it was on previously). Also, the "aSlotTime" value could be adjusted (by an application protocol via the MLME) when propagation maximum delay is known to be bounded. However, the improvements from these actions are likely to be too limited to warrant the extra complexity.

Network Layer. The network layer must provide multi-hop routing functionality capable of supporting the traffic and topological dynamics during the formation process. For PFF, topological changes are slow and well controlled, converging toward to a static formation; network traffic patterns are highly predictable, consisting of low-bandwidth navigation telemetry exchanges between neighboring spacecrafts during the early phases and low delay-jitter, high-bandwidth control loop when in tighter formation. Given the slow dynamics in network topology and traffic pattern and the tight delay jitter requirement, reactive protocols such AODV and DSR are not desirable because they introduce substantial "setup" overhead and delay for every communication attempt.

Instead, a proactive approach where the network maintains its routing table via periodic link state updates is suitable for PFF networking. The required frequency of routing table update is low for a slow changing network, and the "setup" penalty associated with reactive protocols is eliminated. One of the best candidates for routing is OSPF (Open Shortest Path First).

OSPF is a link state routing protocol designed for intra-autonomous system routing for the Internet, and is capable of operating over both switched and broadcast environments (e.g., 802.11's PCF and DCF). For missions with tens of spacecraft, link state is more efficient than the distance vector approach in terms of signaling overhead and rate of convergence. Each spacecraft will implement the OSPF router with IP as the addressing scheme for each spacecraft interface. OSPF provides the mechanism for discovery and synchronization of topology information via HELLO and Link State Advertisement (LSA) messages. As more network connections are formed, a "designated" router and backup router are selected to controls the adjacency of the LSA graph to reduce network traffic and size of topological database. By properly configuring the interface priority and router ID, the leader spacecraft will always be selected as the designated router that controls collection/dissemination of the topology database in a connected network.

It is envisioned that no modifications of the standard OSPF implementation are required for PFF. For the most part, OSPF will provide routing service transparent to the Application Protocol. The Application Protocol on the leader spacecraft may issue query command to its own router, which is the designated router with the latest topology information, for the latest topology information in order to determine when a star topology has been established for the transition to phase five.

Application Layer. A new protocol will be designed for the PFF application, which provides the interface enabling communications status changes to be signaled to the application, as well as reconfiguration of the protocols through the management plane. The rationale for the application layer is that in general a PFF mission is fundamentally dependent on the underlying communications network, requiring formal interaction between the communications network and the PFF application. The applications protocol is described in detail in the next section.

4. APPLICATION PROTOCOL FOR PFF

The application layer protocol is defined in terms of system states (phases) and system state transitions. At any given time instance, it is possible for different spacecraft to be in different phases. The 7 phases and the protocol's behavior are described below:

Phase 0 (initial phase, isolated spacecraft)

Initially, each spacecraft is "randomly" deployed, and in an isolated communications state. The application protocol will generate broadcast discovery messages periodically in order to seek other spacecraft within its

available, so that higher rate application traffic may be generated. If the PFF formation control application decides to reconfigure the formation, it will signal the application protocol so that graceful reduction in bandwidth can take place. This signaling will cause the application protocol to place the network in Phase 4, with the leader broadcasting to all other spacecraft to reactivate multi-hop routing and revert to DCF.

5. MAC PERFORMANCE ANALYSIS

IEEE 802.11 has two different access methods: Distributed Coordination Function (DCF), and Point Coordinator Function (PCF). DCF is suited for ad hoc networks where there is no clear network infrastructure. PCF is more suited for infrastructured network where there is a unique point coordinator.

Distributed Coordination Function

The basic access method in IEEE 802.11 is DCF which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to mediate access to a shared medium. Communication occurs in a time-slotted fashion. When a node wishes to send a data frame, it senses the medium. If the medium is idle for a minimum of DCF interframe space (DIFS) period, the frame is sent. However, if the medium is busy, the node will randomly choose a *backoff* time between 0 and CW-1, where CW is the Contention Window. After the medium is detected to be idle for at least a DIFS period, *backoff* is decremented by one for each time slot that the medium remained idle. If the medium becomes busy during the backoff process, the backoff process is paused, and it will resume when the medium is sensed to be idle for a DIFS again. As the *backoff* count reaches zero, the data frame is transmitted. A collision can occur for this transmission. If a collision occurred, the acknowledgement frame for the data frame will not be sent. When a node detects a missing acknowledgement frame, it doubles its contention window; this is a binary slotted exponential backoff. Let j be the jth attempt to send a data frame, then the contention window is:

$$CW_j = 2^{k+j-1} - 1$$

Where k is a constant defining the minimum contention window $CW_{min} = 2^k - 1$. A new *backoff* is chosen and the backoff process is repeated. Upon successful transmission, the contention window is reset to CW_{min}. The backoff process is also used by a node after a successful data transmission and before it sends the next data frame.

Point Coordination Function

In PCF, it is assumed that a network structure is in place where there is a unique Point Coordination (PC). The medium access is coordinated by PC in a centralized, polling fashion. When PCF is used, the superframe contains a contention free period using PCF and a contention period using DCF. The superframe is started by the PC sending a beacon frame in DCF to start the contention free PCF period. During the contention free period, PC polls frames from each node to coordinate shared medium access. To ensure that PCF is not interrupted by DCF nodes, PCF uses an interfame space PIFS that is shorter than DIFS. To avoid starvation among the nodes that have data to send but were not able to send during the contention free period, every contention free period must be followed by a contention period using DCF.

Performance Analysis

In [22], the performance evaluation of the DCF is given assuming ideal channel conditions, finite number of nodes, and accounts for all the exponential backoff protocol details. The key in their approximation model is the assumption of constant and independent collision probability of a packet transmitted by each station, regardless of the number of retransmissions already suffered. The theoretical analysis has been validated by simulations. The normalized system throughput S is:

$$S = \frac{P_s P_{tr} E[P]}{(1 - Ptr)\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s) T_c}$$

where:

- P_s = the probability that a transmission occurring on the channel is successful is given by the probability that exactly one station transmits on the channel.
- P_{tr} = the probability that there is at least one transmission in the considered slot time.
- $E[P]$ = the average packet payload size
- T_s =average time the channel is sensed busy because of a successful transmission.
- T_c =average time the channel is sensed busy by each station during a collision.
- σ = duration of an empty slot time.

Using a communication range from 0.3 – 1000 km, we obtain the following saturation normalized throughput. Figure 2 shows the plot of distance in kilometers versus normalized throughput S according to the above formula. The plot uses distances ranging from .3km to 1000 km. As the distance increases, the throughput decreases. However, the rate of degradation tends to taper off as the distance increases. In contrast to the quadratic space loss in Physical layer, 802.11 MAC degrades gracefully. It has been shown that 802.11 MAC works well in terrestrial mobile networks when the distance between communicating stations are limited to around 300m. One of the concerns in adapting 802.11 MAC to space applications is whether it will work well with large distances. This analysis shows that 802.11 MAC can be suitable for space applications because the degradation is not sharp as distance increases.

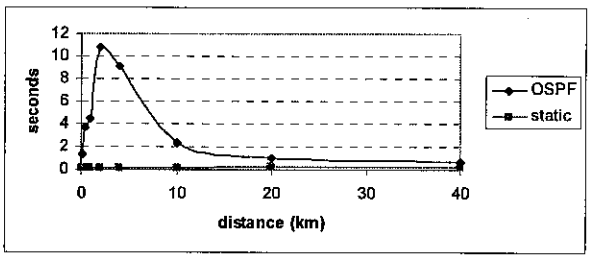

Figure 5: Jitter vs. Spatial Extent
(ring of 8 spacecraft scenario)

Figure 6 shows that when static routes are used, throughput decreases as distance increases; matching the previous theoretical analysis. When OSPF is used, throughput decreases at distance > 4 km. From these results, we determined that by turning off OSPF and use static routes after the spacecraft are in formation will minimize jitter and higher throughput. It is logical that when the spacecraft are in formation, the communication topology rarely changes and there is no need for route discovery; thus we can eliminate the traffic overhead arising from periodic route discovery.

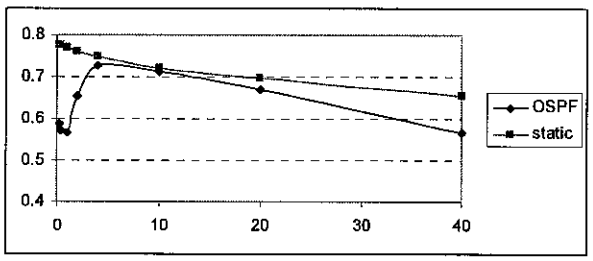

Figure 6: IEEE 802.11 DCF throughput vs. Spatial Extent
(ring of 8 spacecraft scenario)

PCF Performance

We did not simulate IEEE 802.11 MAC (PCF). However, we refer to the simulation results from [9] to motivate our choice of utilizing 802.11 MAC in our application protocol. In [9], the metrics used to measure performance are delay and throughput. The traffic is of two types: best-effort and real-time; the aggregated traffic saturates the network capacity. It was found that in DCF, delay increases exponentially when the load reached 60% (2 Mbps data rate) and 75% (11 Mbps data rate). In contrast, delay remained constant in PCF until the load reached 80%. There is a cross-over point, at 66% load, that PCF has lower delay than DCF. The number of stations also influences delay. As the number of stations increases, CSMA medium-access becomes less efficient and it may be advantageous to switch from DCF to PCF.

In terms of throughput, it was found that DCF has a 83% thorughput for both 2 Mbps and 11 Mbps data rates. PCF provides at least a 4% increase in throughput, at 87% for 2 Mbps data rate and 89% for 11 Mbps data rate. Even though a centralized PCF medium access intoduces additional coordination protocol overhead, PCF still outperforms DCF during heavy traffic loads.

7. Conclusions and Future Work

In this paper, we presented a network architecture to support precision formation flying (PFF) missions. Such missions are critically dependent on knowledge of the underlying communications, which is itself dependent on the spatial distribution of the spacecraft. An application layer protocol is presented that facilitates the necessary signaling between the PFF formation control application and the underlying protocol layers. The network architecture accommodates the significant topological and traffic dynamics inherent to a PFF mission. A single shared physical channel is used in order to scale across missions consisting of up to tens of spacecraft. The IEEE 802.11 MAC protocol is selected as a candidate at the data link layer, as it can provide both robust random access needed during for discover during initial deployment and time-bounded service during precision formation control. Both theoretical analysis and simulation results of the IEEE 802.11 MAC protocol are presented for PFF context, considering both DCF and PCF modes. We have also considered the effects of routing protocols on the jitter and throughput. It was shown that DCF MAC suffers acceptable degradation at the large distances that can arise in PFF missions.

The challenge remains to develop the appropriate physical layer for PFF networks. While numerous 802.11 physical layers have been and are continuing to be defined (e.g., ongoing 802.11n), the space domain poses wide variation in signal levels, wide spatial coverage, and potential large doppler. Integration of the communications with position sensing system is also likely to present considerable system efficiencies. While the 802.11 MAC was assumed in the presented architecture, the application protocol defined could be used with alternative MAC protocols. The design focused on assumptions of centralized formation control, consideration of decentralized formation control systems may be warranted as they may offer advantages in performance and fault tolerance.

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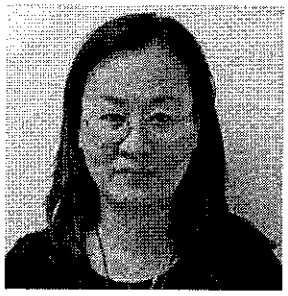

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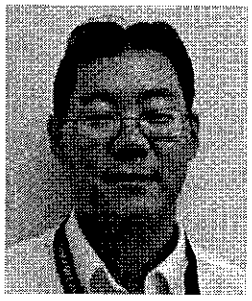

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