OPTIMAL MULTIPLE ACCESS PROTOCOL FOR INTER-SATELLITE COMMUNICATION IN SMALL SATELLITE SYSTEM

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ABSTRACT

The concept of multiple satellite missions is becoming attractive because of their potential to perform coordinated measurements of remote space with greater temporal and spatial resolution, which can be classified as a sensor network or generally as Cyber-Physical System (CPS). Multi-satellite missions require a reliable and cohesive network between the small satellites. This paper represents our initial work on developing an inter-satellite communication link (ISL) that takes into account the symbiotic behavior amongst the system of satellites.

The Open Systems Interconnection model (OSI) will be used as a framework for ISL. The data link, in particular the Multiple Access Control (MAC) layer, will be our primary focus. This paper discusses the communication design issues of PNSats within a sensor network construct. A hybrid combination of Time Division Multiple Access (TDMA)/Code Division Multiple Access (CDMA) scheme for a cluster of satellites is proposed. It consist of a TDMA-centric and a CDMA-centric approach which will address the problem of multiple access in heterogenous small satellite networks, where agents have different data transmission rates. This method can also extend the application of small satellite networks in terms of scalability. We will validate through simulations that the CDMA-centric achieves high throughput with minimum delay.

1 INTRODUCTION

Small satellites revolutionized the aerospace industry by changing the concept of historically expensive space missions. Using small satellite systems, more and more countries around the world are trying to develop their own space capabilities with reduced costs and more efficiency out of smaller configurations. This trend for small satellites was originally adopted by universities in their limited budget and consequently it gained popularity in government agencies and industrial sector. The developments of small satellite systems are driven by two main factors – the need to reduce the cost to access space and the advancements in microelectronics. Small satellites make utilize Commercial Off-The-Shelf (COTS) components as much as possible, hence take shorter time from development to launch. Small satellites have a mass of less than 1000 Kg [1], [2] and [3]. It is broadly classified into different classes, namely, mini-, micro-, nano-, pico-, and femto- depending on their mass as illustrated in Table 1. The primary focus of our research is in the nano and pico class of satellites.

Table 1. Classification of small satellites

Type of satellite	Mass
Mini	< 500 Kg
Micro	< 100 Kg
Nano	< 10 Kg
Pico	< 1 Kg
Femto	10 g–100 g

Multiple satellite missions are a new trend of research in the space industry. Multi-satellite solution is highly economical and helps to provide improved spatial and temporal resolutions of the target. For future space missions, a large number of heterogeneous small satellites can be deployed in space as a network with minimum human intervention and thus demanding a need of Inter-Satellite Link (ISL). The PROBA-3 [4] and QB-50 [5] are some examples of missions using a group of small satellites with inter-satellite links. The PROBA-3 is a science mission managed by European Space Agency (ESA) using low-cost small satellites. It consists of two satellites having a mass of 350 Kg and 200 Kg flying in formation with a relative separation distance ranging from 25 m to 250 m in a highly elliptical orbit which will demonstrate the technology required for formation flying of two or more space crafts. Inter-satellite communication provides information flow between the small satellite systems to enable advanced functions, for example, distributed processing, servicing or proximity operations, autonomous applications, etc. Inter-satellite communication helps to eliminate the use of extensive ground based relay system and worldwide tracking systems [6]. It also helps to provide attitude control and timing synchronization. It is also possible to maintain the relative distance between the small satellites using ISL.

There are several researches being conducted on inter-satellite communications for small satellite systems. The QB50 project is a multi spacecraft network of 50 CubeSats carrying identical sensors for in-situ measurements in the lower thermo sphere built by university teams all over the world. In [7], the authors propose the possibility to implement the Transmission Control Protocol (TCP) and (User Datagram Protocol) UDP over Internet Protocol (IP) through inter satellite links and distributed ground stations. However the TCP/UDP protocol corresponds to the transport layer which is used in Ethernet and Internet applications. They have not mentioned the protocol they have used for medium access (i.e., the MAC layer protocol). In TCP/IP reference model, for data link layer, the CSMA/CD protocol is used which is suitable for wired networks. Therefore, the TCP/UDP protocol will not be a good choice for inter-satellite communication of small satellites.

The Open System Interconnection (OSI) model serves as a reference for the communication between different computer systems connected in a network. The OSI model is a system that helps to breakdown network functions. It can be used as a framework for inter-satellite communication for small satellite systems. The OSI model has seven layers and each layer has well defined functions. The second layer, i.e., the Data link layer, is the primary focus of our research. This layer is responsible for physical addressing (Medium Access Control/MAC address) and also ensures error free data transmission. The MAC layer provides channel accessing schemes for several nodes within a multiple access network that uses a shared medium.

The performance of the IEEE 802.11 standard for Lower Earth Orbit satellites is investigated in [8] and [9]. A modified IEEE 802.11 Medium Access Control protocol is proposed which is based on a contention based protocol, i.e., Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The four way handshaking mode using CSMA/CA with Request-To-Send (RTS) and Clear-To-Send (CTS) is investigated for inter-satellite communication. However, contention based

MAC protocols will be inefficient under the condition of high contention. When the number of satellites in the whole system becomes large, the overall access and end-to-end delay will be substantial which is not suitable for missions that require tight communication links for example, servicing or proximity operations. In [10], a hybrid combination of contention and scheduled based protocol is investigated for inter-satellite communication. A contention based MAC protocol, CSMA and slot-based mechanism TDMA is combined and a new protocol, Load-Division Multiple Access (LDMA) is proposed. For LDMA protocol, a node is in two modes: Low Contention Level (LCL) or High Contention Level (HCL). For LCL, it behaves like CSMA and for HCL, it acts in TDMA mode. The LDMA protocol is an ideal choice for a system with less number of satellites. It will not be able to perform satisfactorily in a scalable network of small satellites. If the system consists of a large number of small satellites, TDMA protocol will not be appropriate as clock synchronization will be challenging. Precision Formation Flying (PFF) missions require small satellites in a desired relative geometric configuration which can be achieved using inter-satellite communication and relative navigation. In [11], the capability of using half-duplex/full-duplex CDMA with roles rotating architecture for PFF missions is analyzed.

The small satellite system typically consists of multiple mobile nodes forming a dynamic network topology with intermittent communication links. Small satellites have limited on board power and computing resources. The design of the multiple access protocols largely determines the performance of the entire system. In this paper, a novel hybrid TDMA/CDMA protocol for multiple access is proposed for inter-satellite communication for small satellite systems. The Frequency Division Multiple Access (FDMA) is not an economic choice as it requires a larger bandwidth. The TDMA allows collision free transmission while CDMA enables multiple users to transmit simultaneously using their own Pseudo Random Noise (PRN) codes. The TDMA protocol that we propose is adaptive rather than fixed time slots to each user thus utilizing the channel effectively. We have investigated the combination of TDMA with Direct Sequence CDMA (DS-CDMA). The advantages of using DS-CDMA are better noise and anti jam performance and also it offers inherent privacy. This is due to the fact that the PRN code sequences will be known only to the transmitter and receiver nodes. The proposed protocol is analyzed using three different parameters throughput, average access delay and average end-to-end delay respectively.

The rest of this paper is organized as below. Section 2 briefly gives the overview of MAC protocols. A brief description of the proposed protocol is described in Section 3. The simulation results are discussed in Section 4 and the paper is concluded in Section 5.

2 OVERVIEW OF MAC PROTOCOLS

A typical scenario in a wireless sensor network consists of a large number of nodes that need to communicate using a single channel. Generally, transmission from any node can be received by all other nodes in the network. Therefore, if more than one node in the network attempts to transmit at the same time, a collision occurs, which will result in the loss of the data packet. The receiving node cannot interpret the data which is being transmitted and such situations are called collisions or multiple access issues [12]. In order to avoid collision, the nodes in a network should follow some set of rules or protocols that would allow fairness among the nodes for accessing the channel and also will result in the effective utilization of the channel. The basic function of MAC protocols is to avoid collision by arbitrating the access of the shared medium among the nodes in the network. In order to improve the performance of the network, MAC protocol should also consider several factors, including scalability, adaptability, channel utilization, latency, throughput, and fairness [13].

There are two different types of multiple access protocols for handling collision of data packets, contention based and conflict-free protocol

- Contention based - According to this protocol, nodes compete for the channel and when a collision occurs, the protocol carries out a collision resolution protocol. Numerous contention based protocols have been proposed in the literature for example, ALOHA, CSMA (Carrier Sense Multiple Access), BTMA (Busy Tone Multiple Access), ISMA (Idle Signal Multiple Access) etc.
- Collision-free - The collision free protocols ensure that collision of data packet never occurs. Some of the basic protocols of this type are TDMA (Time Division MA), FDMA (Frequency Division MA) and CDMA (Code Division MA). The OFDMA (Orthogonal Frequency Division MA) and SDMA (Space Division MA) are other two variations which have been introduced recently.

2.1 Collision Free Multiple Access Protocols

Contention free multiple access techniques are based on the orthogonality of the radio signals. A radio signal can be mathematically represented as a function of frequency, time and code. If each node in the network uses different carrier frequency, it is a FDMA system. If the system uses distinct time slots for each node, it is a TDMA system. If each node uses different codes, it is a CDMA system. Conflict-free protocols can be used in real time applications for its ability to ensure fairness among all users and also its capability to control the delay of the data packets.

2.1.1 Time Division Multiple Access

In the TDMA scheme, a single carrier signal is split into time slots which will be assigned to different users. Each user transmits during its allocated time slot and during that period the entire resources of the system are devoted to that user. Using TDMA, it makes it possible to effectively utilize one frequency for all the users provided that each user utilizes different time slot. The time slots are assigned to the users in a predetermined manner which repeats periodically after every *cycle* or *frame*. In basic TDMA, each user is allocated exactly one slot, but in a more general TDMA scheme, several slots will be assigned to each user**.** A TDMA system will work in either of two modes; TDMA/FDD (Frequency Division Duplexing) where uplink and downlink communication frequencies differ and TDMA/TDD (Time Division Duplexing) where both uplink and downlink use the same frequencies. Figure 1 shows a TDMA/TDD frame structure.

In TDMA, the time slot allocated to a user does not depend on whether or not the user has any data to be transmitted. Extended Time Division Multiple Access (ETDMA) attempts to overcome this problem by allocating time, according to need [13]. Extended TDMA uses idle times in a conversation to transmit. When a user has data to be transmitted, they put one bit in the buffer. The system scans and notices the buffer and allocate resources to that particular user accordingly. This scheme increases the efficiency significantly when the partners in a conversation do not speak over one another.

Time Division Multiple Access ensures interference free transmission unlike other multiple access schemes since the users are separated in time. It can handle both voice and data communication. Another advantage of TMDA is extending the users' lifetime as they only transmit in a portion of time. This fact makes TDMA an ideal candidate for applications with limited available power. It is relatively less expensive to set up a TDMA base station compared to other protocols [13] since compared to FDMA, the base station is not required to support multiple frequencies. The disadvantage of TDMA is its difficulty to accommodate new users in the system and also TDMA system needs strict timing synchronization. Moreover, in TDMA method, the data transmission of users is not continuous over time and this might impose an intolerable delay in the system.

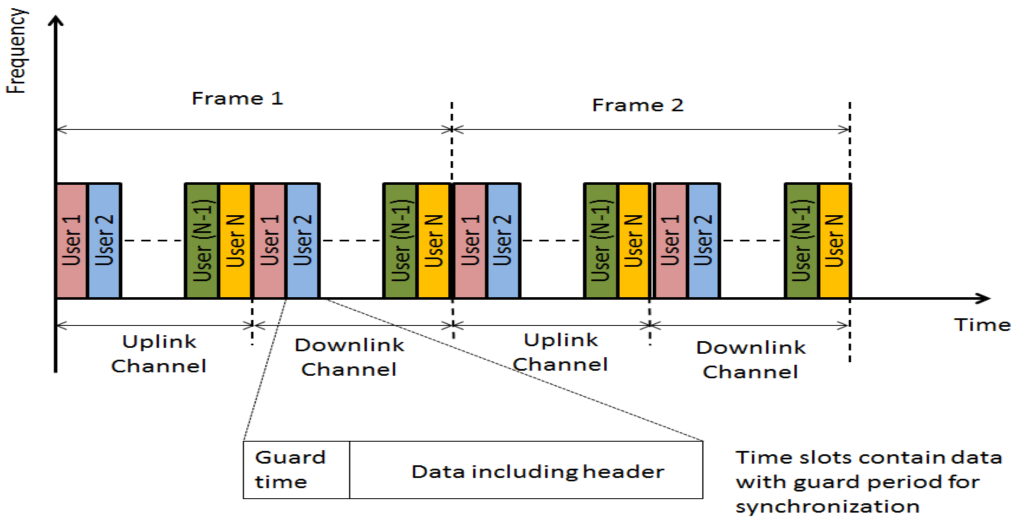

Figure 1. TDMA/TDD Frame structure

2.1.2 Code Division Multiple Access

The CDMA protocols are placed between contention less (FDMA, TDMA) and contention (ALOHA, CSMA) protocols because of its ability to achieve synchronous communications, the users can transmit using the same frequency and it is possible for two or more nodes to transmit simultaneously. A CDMA system can overcome the typical communication issues (multipath fading, shadowing, near-far effect, etc.) depending on the type of CDMA used [14]. It uses spread spectrum technology using different codes to separate users, rather than different frequencies or time slots as compared to other access schemes hence providing significant improvements in overall system performance and spectrum efficiency. Figure 2 shows a CDMA system.

There are a number of modulation techniques that can be used to generate spread spectrum signals. In the DS-CDMA, the data signal is directly multiplied by the code signal and modulates the wideband carrier. The code signal consists of a number of code bits or chips, that can be either +1 or -1. For a wider bandwidth signal, the chip rate of the code signal has to be much more than the information. Various modulation techniques can be used, but usually some form of the Phase Shift Keying is used, e.g., BPSK, QPSK, etc. On the receiver side, the received signal is despread using locally generated code which must be synchronized to the code sequence of the received signal. The synchronization should be achieved at the beginning of the received signal and has to be maintained throughout. In Frequency Hopping CDMA (FH-CDMA) scheme, the carrier frequency is not constant and changes after each time interval T. The hopping pattern is determined by the code signal. The DS-CDMA system occupies the whole bandwidth for transmission, whereas FH-CDMA uses only a small part of the bandwidth that differs in time. The transmitter frequency hops from channel to channel in a predetermined manner. The received signal is dehopped using the frequency synthesizer synchronized to the transmitter's pseudorandom sequence generator. There are two types of FH-CDMA: Fast hopping where there are multiple hops per bit and slow hopping where there are more bits per hop. In Time Hopping CDMA system, the data signal is transmitted in bursts at time intervals determined by the code assigned to the user. The time axis is divided into frames and each frame has N slots. Each user transmits on one of the N slots, depending on the code assigned to the user. Hybrid CDMA systems employ a combination of two or more of the above mentioned spread spectrum techniques, for example, DS/FH, DS/TH, FH/TH and DS/FH/TH.

Hybrid systems make use of the specific advantages of each of the modulation techniques even though it increases the complexity of the transmitter and receiver.

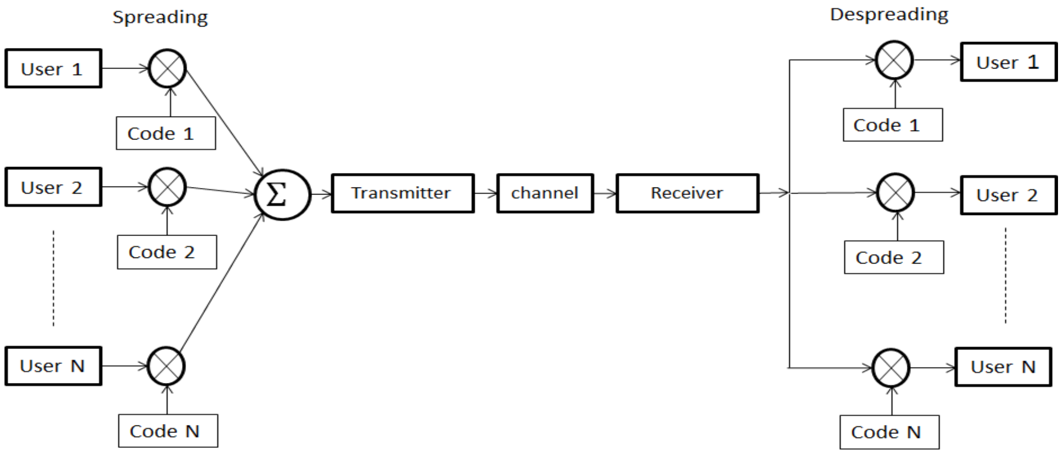

Figure 2. A CDMA System

3 THE HYBRID TDMA/CDMA PROTOCOL

The space environment is dynamic and/or unpredictable, networking multiple spacecrafts for a heterogeneous system could be difficult, leading to delayed or disrupted communication links. Space communication experiences intermittent connectivity, where there may not be an end to end path between the source and destination and also long or variable delay may occur between satellites. For future space missions, small satellites may be deployed in different phases in order to accomplish a mission objective, for instance, the FORMOSAT-7/COSMIC-2 [15] is a Taiwan/USA project, which is scheduled to launch in two phases in 2016 and 2018. This will use a constellation of 12 small satellites to collect meteorological and ionospheric data with better precision with respect to FORMOSAT-3/COSMIC-1. Also, the small satellite network may have unexpected failures. Considering all these objectives, the small satellite network can be divided into clusters to achieve the networking scalability objectives and achieve high energy efficiency. The clusters may be overlapped or non-overlapped and for the clusters to communicate with each other, we are proposing to implement master slave model with each cluster having a master satellite and several slave satellites as shown in Figure 3.

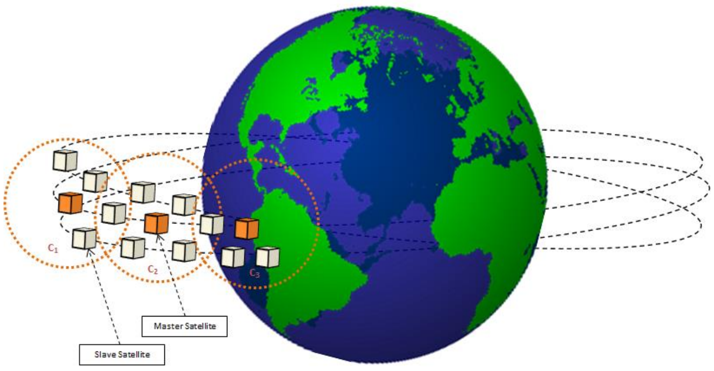

Figure 3. Overlapped Cluster of Small Satellites

The members of the clusters will send the data to their respective master satellite and the master satellite forwards the aggregated data to the destination through other master satellite. If the member satellites within a cluster are within the transmission range of each other, we are proposing that the members can communicate directly with each other without communicating with the master satellite. The master satellite has to cover the entire cluster and also needs to transmit the data over long distances, it may lose more energy compared to member satellites. Hence, it is necessary to recluster the network in order to select the master satellite with enough power for communication.

We propose to use the centrality algorithm for the selection of master satellite within a cluster, provided it satisfies the minimum power requirement (threshold, P_{th}) and also it can do beam forming using smart antennas to increase its coverage range.

3.1 Centrality Algorithm

The centrality algorithm is an important concept in graph theory and network analysis [16]. Centrality of a node measures the relative importance of that node in a network. There are four main measures of centrality: degree, betweenness, closeness, and eigenvector.

- Degree centrality is defined as the number of connections incident on a node. For a directed graph there are two types of degree centrality i.e., indegree and outdegree centrality. The indegree centrality of a node is the fraction of nodes, it is connected to and outdegree is the number of links that the node directs to others.
- Closeness centrality of a node is the distance to all other nodes in a network. The more central a node is the lower distance to all other nodes and thus takes less time to spread information.
- Betweenness centrality is defined as the measure of the number of times a node act as a router along the shortest path between two other nodes. There is also edge betweenness which is the sum of the fraction of all-pairs shortest paths that pass through an edge.
- Eigenvector centrality is defined as a measure of the influence of a node in a network.

For our system model, we aim to use the closeness centrality algorithm using which the master satellite can be chosen based on the distance to all other satellites in a network. This distance parameter will be determined by communication signal power. Master satellite need not have to be modified periodically as in the case of wireless sensor networks, thus avoiding periodic updates to the cluster members and thereby less communication overhead. Nevertheless, due to harsh environmental conditions, it is probable that the master satellite may fail to function in which case, we can run the centrality algorithm again to obtain the new master satellite.

3.2 Proposed Work

In this paper, we investigate the combination of TDMA with DS-CDMA technique. In a TDMA system, each time slot can be used by one satellite at any given time, whereas, a CDMA system allows multiple satellites to share the same channel simultaneously in the time and frequency domain using their unique DS codes. The codes are orthogonal i.e., the cross correlation between any two codes should be ideally equal to zero. Satellites in several clusters can transmit in the same time slot using their unique codes. The Walsh-Hadamard or Gold sequences can be used for generating perfectly orthogonal codes [17]. Each cluster can be assigned a different set of codes thereby avoiding interference between clusters. We propose to use Time Division Duplexing since uplink and downlink can use the same frequency for transmissions. The motivations of using hybrid TDMA/CDMA are the following:

- For hybrid TDMA/CDMA protocol, it is possible to design a small satellite network where the strength and weakness of both protocols may be traded off against each other to match the design requirements.
- It allows for the integration of different traffic types using coded transmission.
- All the satellites can transmit simultaneously in its allocated time slot using its unique code thus avoiding interference.
- For a pure TDMA system, the addition of more satellites will be an issue which can be overcome using CDMA technology based on clustering thus supporting a large scalable network.
- Depending on the packet size, an adaptive TDMA can be used rather than fixed slots, where a variable number of slots are allocated depending on the size of the data packet provided there is a good control channel allocation. The cluster head must inform the members to refrain from using their slots in order to avoid collision.
- Unlike pure CDMA, time scheduling can be used to control interference between codes thus ensuring high quality of service.
- It is suitable for space missions that require tight communication links, for example, servicing and proximity operations.

A CDMA system has several limitations like cross correlation and the near-far effect. Cross correlation results from the non-perfect orthogonal PRN codes. This will cause multiple access interference which can be avoided by restricting the number of satellites in each cluster [11]. The near-far effect can be mitigated by appropriate power control mechanism. The suggested protocol requires strict time synchronization which can be achieved by using GPS/GNSS clock or clock synchronization in conjunction with a highly accurate on-board clock.

3.2.1 Frame Structure

For the proposed protocol, time is divided into fixed size frames, which in turn is divided into slots. The combined TDMA/CDMA system can be implemented in two different ways. In both cases, to avoid the complexity of the system, the satellites cannot be at the transmitting and the receiving stage at the same time. Also, it is assumed that the transmitting satellite can transmit a single signal from a member satellite at a particular time slot.

- TDMA Centric – In this case, each cluster is allocated a unique code and each satellite within a cluster has a dedicated slot. The satellites communicate with the master satellite in its allocated time slots using uplink slots and master satellite transmits the data packets in the downlink slots. The master satellites need its own uplink and downlink slots for communicating with the neighboring master satellites. Figure 4 shows the frame structure for TDMA centric hybrid protocol. Multiple clusters can transmit in the same frame using different codes avoiding interference. The master satellite can receive the signals from neighboring master satellites in one downlink slot as the CDMA receiver can distinguish between the signals based on the unique DS code. The TDMA centric hybrid protocol can be used in missions where the packet size varies considerably.

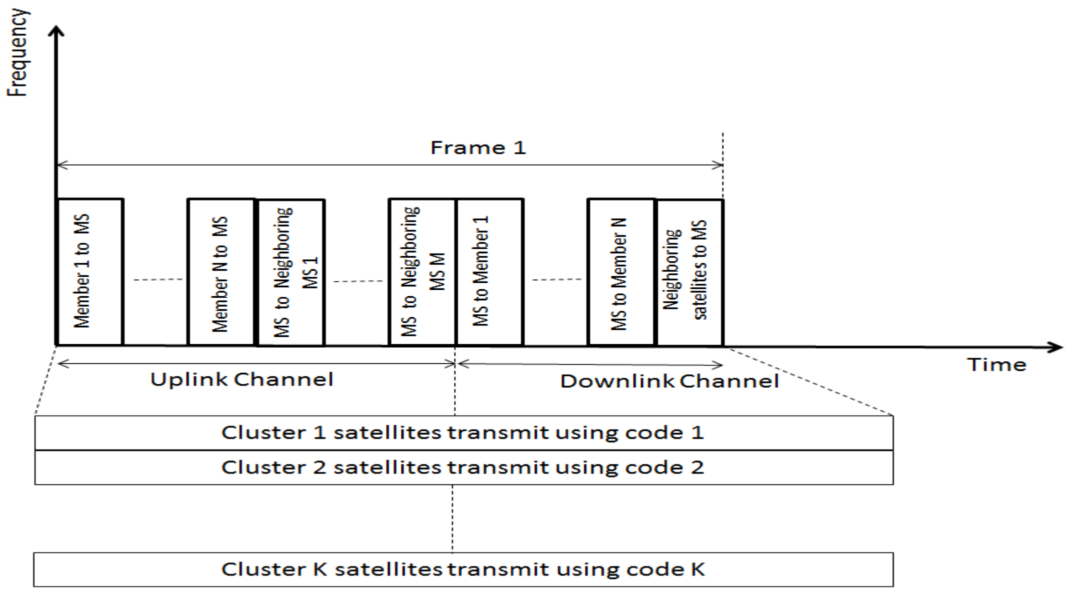

Figure 4. The frame structure of hybrid TDMA/CDMA system (TDMA Centric)

- CDMA Centric – In a CDMA centric hybrid protocol, each satellite in the system is assigned a unique code. The frame structure for a CDMA centric hybrid protocol system is shown in Figure 5. In the first slot, the members in all clusters can transmit to the master satellite simultaneously without interference using their own orthogonal codes. For the master satellite, there are dedicated slots to transmit data to the neighboring master satellites. Similarly for downlink, master satellite communicates with its members in its own dedicated slots. It can receive data from the neighboring satellites in the downlink slot. The CDMA centric system can be used if the packet size is relatively consistent and also for missions where it is required to broadcast some important information to the cluster members.

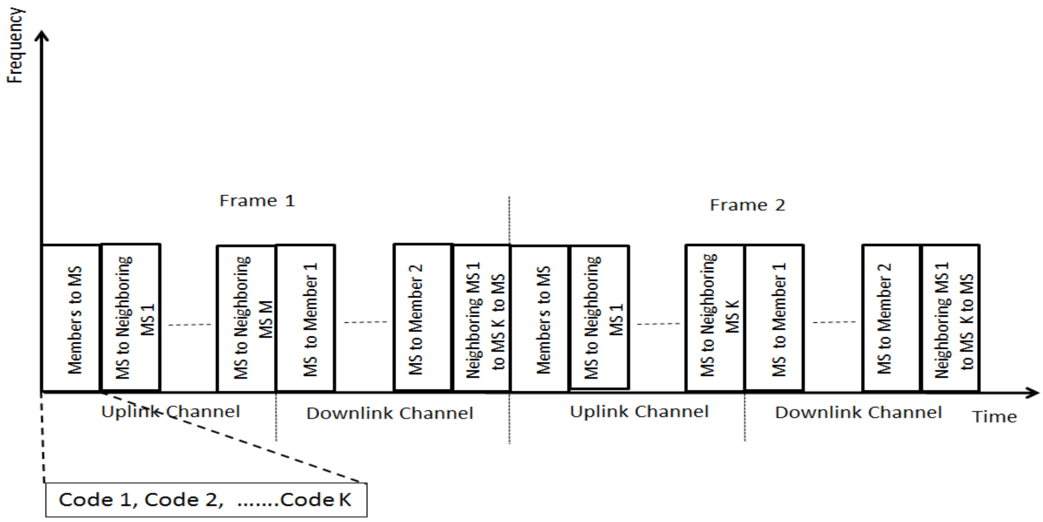

Figure 5. The frame structure of hybrid TDMA/CDMA system (CDMA Centric)

4 SIMULATION RESULTS AND DISCUSSIONS

We will illustrate the capabilities of our proposed work (using a CDMA centric frame structure) based on measurements of throughput, average access delay and average end-to-end delay. For simplicity, the Leader-Follower formation flying pattern of small satellites will be used. In Leader-Follower pattern, multiple spacecrafts will be orbiting the Earth in the same orbit separated from each other at a specific distance. Let us assume N slave satellites per cluster with a total of K clusters. Also, we assume that there are M neighboring clusters. Each satellite communicates with its master satellite in its dedicated slot using its unique code. If a satellite in one cluster has to transmit information to a satellite in another cluster, it first sends the packet to the master satellite, then the master satellite transmits to the destination through other master satellites. The proposed model and data flow from a source satellite to a destination satellite are illustrated in Figure 6.

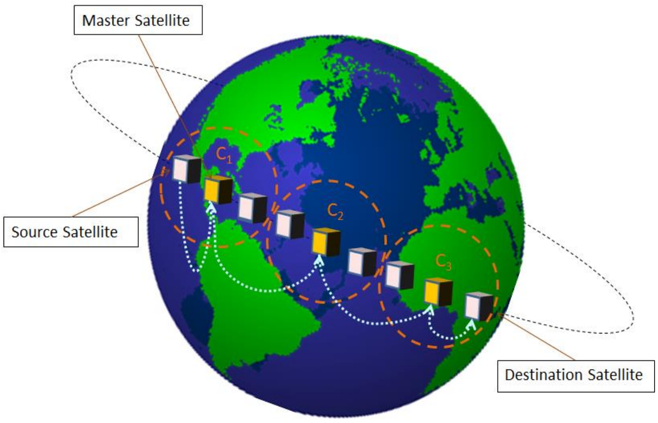

Figure 6. Simulation Model

We have simulated the CDMA centric frame structure using the parameters shown in Table 2. We use these parameters as part of our simulations, but they represent possible mission parameters that our research group might be using in the future and are subject to change.

Table 2. Simulation Parameters

Parameters	Value
Size of cubesats	3 - 6 U
Transmission power	500 mW – 2 W
Orbital shape	Circular (for simplicity)
Number of orbits	1 (for Leader-Follower pattern)
Orbital altitude	Lower Earth Orbit (300 Km)
Number of satellites in each cluster	3
N (Number of slave satellites in each cluster)	2
K (Number of clusters)	3 - 9
M (Neighboring clusters)	2
Transmission frequency	2.4 GHz (ISM/S-band, Unlicensed band, higher throughput)
Orbital velocity	3 Km/s
Inter-satellite range	10 Km (from link budget analysis)
Number of packets simulated	10,000
Packet arrival rate	Poisson distribution
Packet length	Exponential distribution
Slot length	100 ms
Frame length	0.6 s (6 slots/frame)

This proposed protocol is evaluated using different parameters:

- The *throughput* of a system is defined as the amount of time used for a valid transmission.

$$Throughput\,(\%) = \frac{Total\ data\ transmission\ time}{Total\ simulation\ time}$$

- *Access delay* is the amount of time each data packet has to wait before it gets access to the channel.
- *End-to-end* delay is the time each data packet takes to reach from a source satellite to a destination satellite.

We simulated the CDMA centric protocol in Java. To obtain reliable and stable results the simulation runs will consist of 10,000 data packets. Simulations are also constrained by assuming that a satellite cannot generate a new message until all packets of the current message are transmitted completely and a satellite which has generated a message in the current frame cannot try to access the data slots in the same frame. Figures 7 and 8 show the average access delay and end-to-end delay when we increase the number of clusters from 3 to 9 for different packet arrival rates. As we can see from the results, the delays are almost constant (around 0.6 seconds) as the traffic increases. This is because, each data packet has to wait at least one frame long before it gets access to its allocated slot irrespective of the packet arrival rates. It is observed that even if we increase the number of satellites in orbit, access delay is almost the same for all different scenarios. When we increase the number of satellites in the orbit, the end-to-end delay increases as can be seen in Figure 8.

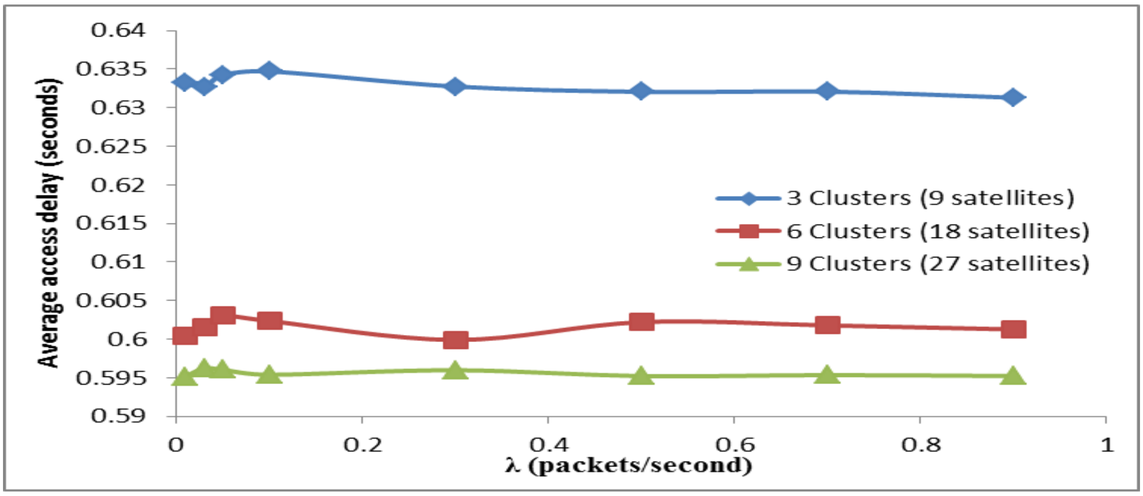

Figure 7. Average access delay

The throughput of the system is inversely related to the access delay and end-to-end delay. As the delay decreases, throughput increases. As can be seen in Figure 9, the throughput is less when the packet arrival rate is low since there will be more under utilized slots in a frame. When the traffic increases, most of the slots in the frame will be utilized for data transmission and thus can have a throughput of almost 100%. Also, for the scenario with 27 satellites in orbit, the system reaches saturation quickly compared to the scenario with 9 satellites since the overall number of packets will be comparatively more for the scenario with 27 satellites thus utilizing the slots more efficiently even for low traffic

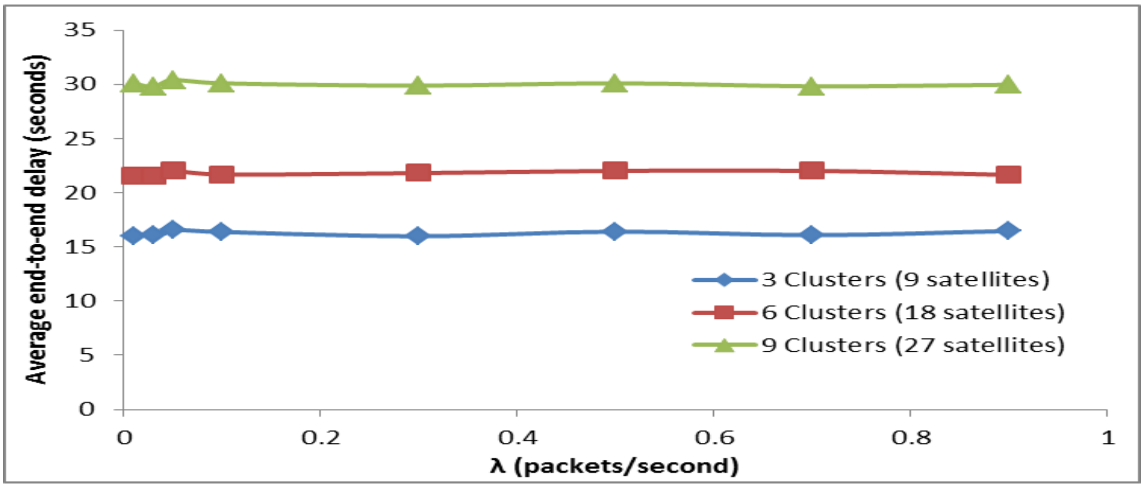

Figure 8. Average end-to-end delay

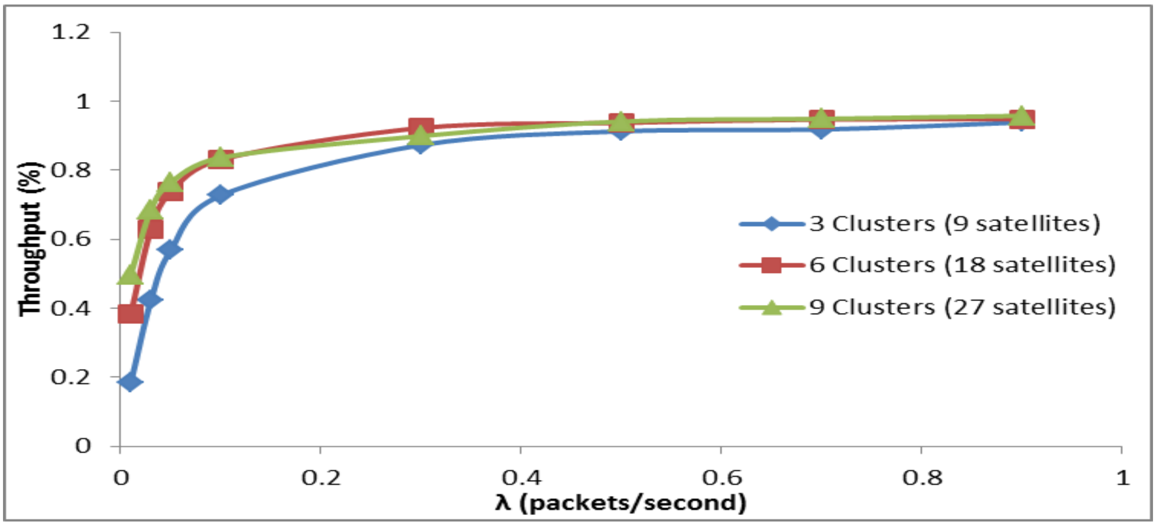

Figure 9. Throughput

4.1 Comparison with CSMA/CA/RTS/CTS protocol

We investigated IEEE 802.11 MAC protocol which is based on a modified CSMA/CA/RTS/CTS protocol for a network of small satellites in [9]. The CSMA/CA/RTS/CTS is a contention based protocol, where all nodes in a network compete for the channel. According to CSMA/CA/RTS/CTS protocol, a node first senses the channel to see if there is any on-going transmission. If it senses that the channel to be idle, it continues transmission. Otherwise, it refrain from accessing the channel for a random amount of time and continues the process. If a node succeeds in getting access to the channel, it informs its neighboring nodes through the RTS/CTS commands so that it can refrain from sensing the channel and thereby avoiding collision and loss of data packets. The performance of this protocol is compared with the hybrid TDMA/CDMA protocol in Figures 10, 11 and 12. As can be seen from Figures 10 and 11, the average access delay and end-to-end delay is more for the CSMA/CA/RTS/CTS protocol because of network congestion at very high traffic. Using hybrid TDMA/CDMA protocols, the satellites have their own allocated slots for transmission in each frame. Therefore, the data packet of each satellite will wait for the next frame for processing and hence minimizing the delays. As the average access delay and end-to-end delay is inversely related to throughput, hybrid TDMA/CDMA protocol has a higher throughput of 95% compared to the CSMA/CA/RTS/CTS protocol with a throughput of 24% for λ = 0.7 packets/second as can be seen in Figure 12.

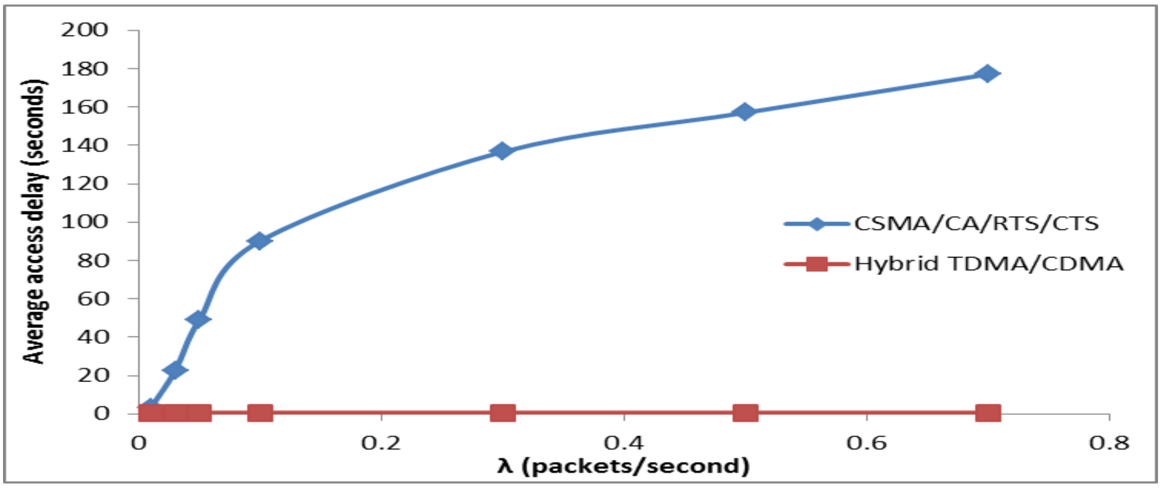

Figure 10. Average access delay comparison

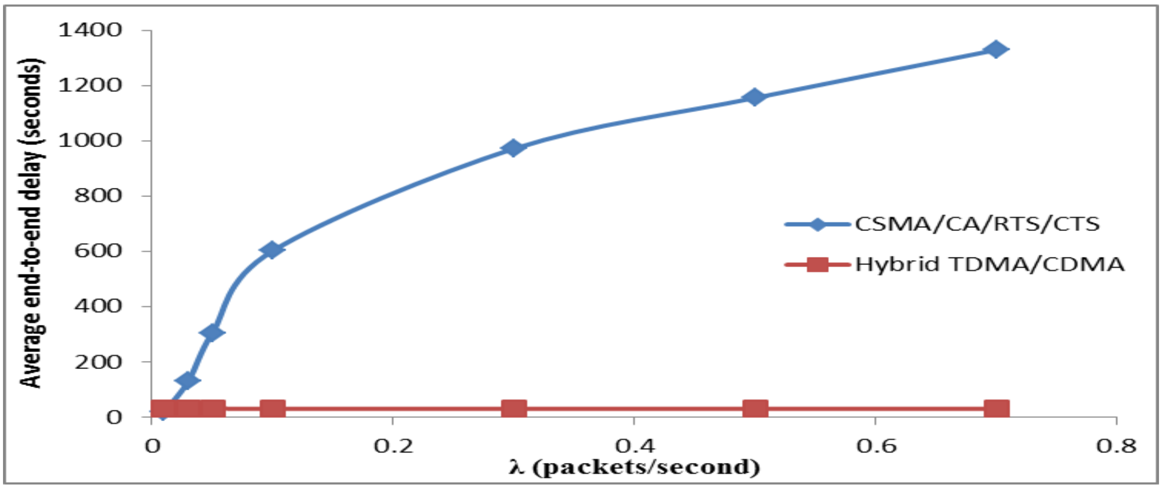

Figure 11. Average end-to-end delay comparison

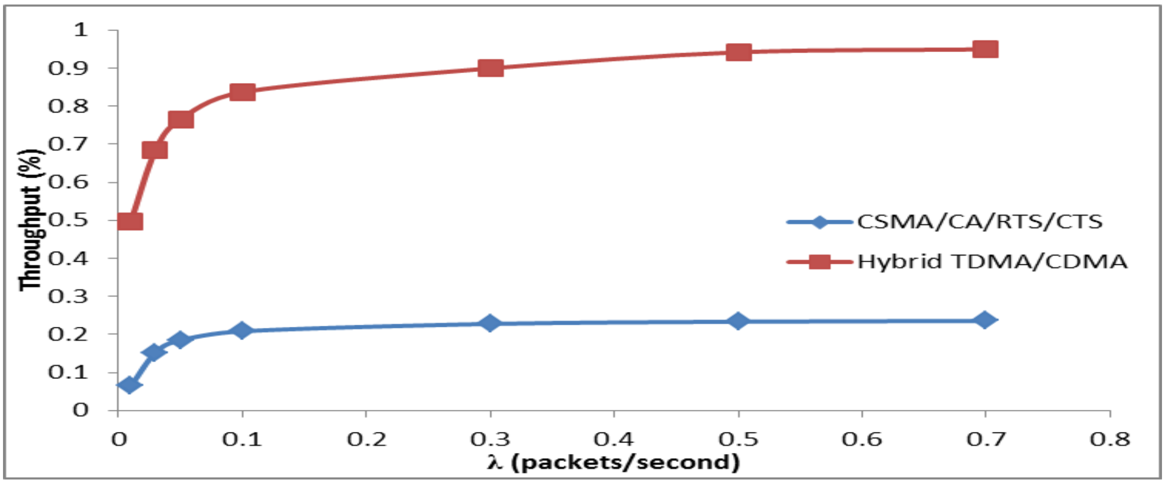

Figure 12. Throughput comparison

5 CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a hybrid TDMA/CDMA protocol for a network of small satellites that addresses the design needs of a large number of small satellites within a reconfigurable network. The hybrid protocol can be implemented in two ways: TDMA centric and CDMA centric. The frame structures for the two different types are also discussed. The proposed protocol offers greater advantages compared to other protocols like CSMA/CA/RTS/CTS and is validated by extensive simulations. In this paper, we have used CDMA centric frame structure. The proposed protocol gives more throughput with less delay compared to other protocols. The decision of which protocol to choose depends on various parameters mainly the application or mission architecture. For missions that require frequent updates with less delay can be designed using hybrid TDMA/CDMA protocol. For a science mission with less number of satellites and that can tolerate very high delays, CSMA/CA/RTS/CTS protocol can be used.

Our future work is to evaluate the performance of the TDMA centric protocol. The use of the hybrid TDMA/CDMA protocol can also be analyzed for various formation flying patterns like cluster and constellation for small satellite systems. For our simulation, we have considered three satellites in a cluster, with one master satellite and 2 slave satellites. In the future, we can analyze the performance of the proposed protocol by increasing the number of satellites in each cluster and also consider the scenario where if the members in a cluster are within the transmission range they communicate directly for various configurations of small satellite systems.

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