Heterogeneous Control and Data Split Network for Precision Formation Flying of Distributed Spacecraft

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Abstract. In order to support Precision Formation Flying (PFF) mission, distributed spacecraft requires inter-satellites communication links with reliable and efficient performance. An optimized Mobile Ad hoc Network (MANET) is used to provide high-quality broadband service with high reliability and system capacity. It separates the whole network into two sub-networks, including a control sub-network in mesh architecture for time-critical control messages, and a data sub-network in Point-to-Multipoint (PMP) architecture for high speed data messages. In this paper, an event-driven Medium Access Control (E-MAC) protocol for control sub-network to deal with PFF high priority messages is proposed. E-MAC protocol is based on the event-driven mechanism: spacecraft adjust the contention parameters to the arrival of primary events and secondary events. Analysis and simulation results indicate that the proposed E-MAC protocol can achieve real-time ability as well as spectrum and energy efficiency.

Keywords: Formation flying · Distributed spacecraft communications · Event-driven · Heterogeneous

1 Introduction

The concept of Distributed Satellites System (DSS) has been intensively researched in recent years, promising revolutionary advancement by enabling the collective use of multiple small mini- or micro-satellites to create a single, large, virtual space borne instrument [1, 2].

Distributed Spacecraft Communications (DSC) system can adopt several technical architectures, such as data link system and MANET [3]. The capacity of the current data link system is limited, and cannot implement high-speed transmission. MANET communication protocols are presented as possible candidates for the future DSC systems [4]. However, it cannot support high-speed real-time data transmissions in DSC system [5].

Generally, there are two kinds of messages in PFF: real-time control messages and massive data messages. Due to the highly dynamic property of PFF network topology, the transmission of control messages should meet low delay, high reliability and omnidirectional coverage. However, data messages have lower latency and should be

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transmitted directionally. In the existing techniques, the mentioned two kinds of messages are coupled in the same channel to transmit, which is of conflict with the requirements above. Besides, in traditional PFF systems, spacecraft may loss contact with the control center due to the constraints of communication conditions or unexpected failure. Therefore, efficient control and data split mechanism (to guarantee the QoS of control messages and high-speed transmission of data messages simultaneously) is needed [6]. In this paper, we present a heterogeneous control and data split network that supports both the instantaneity of control messages and the high-speed transmission of data messages simultaneously at separate channels.

Moreover, when satellites use loose formations flying, DSC requires low QoS of control messages. However, when spacecraft fly in a circular formation, PFF can be easily influenced by environmental factors, which may cause spacecraft in danger [7]. Hence, a proactive scheme is needed for the DSC to deliver such critical messages instantly to the whole DSS. Here, the emergent spacecraft named primary spacecraft which faces the danger of ruin, should have higher priority to access to the network than the other spacecraft named secondary spacecraft. In order to provide different levels of spacecraft with different QoS guarantee, an event-driven MAC protocol named E-MAC is proposed in this paper. Different from IEEE 802.11e which differentiates packets according packet types or protocol classes, E-MAC promotes the priorities just according to whether a triggering event is coming no matter what the packet type is.

The paper is organized as follows. In Sect. 1, the architecture of heterogeneous control and data split network for PFF-based distributed spacecraft is presented. In Sect. 2, event-driven MAC protocol for control sub-network is discussed. In Sect. 3, simulations are carried out to evaluate the performance of the proposed network architecture and event-driven MAC protocol. Finally, conclusions are drawn in Sect. 4 based on the analysis and simulation results.

1.1 Architecture of Heterogeneous Control and Data Split Network for Distributed Spacecraft

As shown in Fig. 1, the architecture of DSC system is a combination of two logical sub-networks: control sub-network for transmitting satellite operational messages as well as signaling messages, and data sub-network for high speed data transmission. Control sub-network is the basis of DSC system, which transmits control data for the whole network to operate. Control messages feature small amount, periodical, omnidirectional transmission as well as highly real-time. Data sub-network deals with payload data, which are of great quantity, and should be transmitted directionally.

1.2 Optimize the MANET Protocol Stack

In IEEE 802.11x, there are two access modes, one is the fundamental contention-based Distributed Coordination Function (DCF), and the other is the optional polling-based Point Coordination Function (PCF).

Since in DCF mode, wireless users have to contend to access the wireless medium, each user has fair opportunity to transmit messages and is strongly adaptable to the

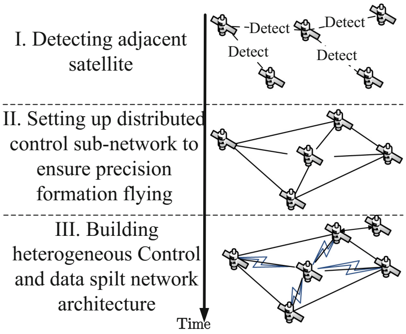

Fig. 1. Network structure of the DSC system.

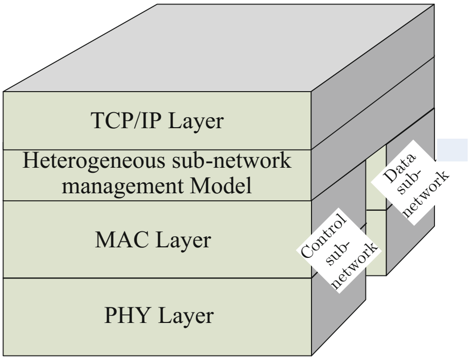

Fig. 2. Optimized MANET protocol stack.

highly dynamic DSC network topology. Control sub-network adopts the decentralized mesh architecture and works in DCF without central coordination node. This structure provides multiple end-to-end transmission paths, and the redundancy of the paths can assure that operational control packets can reach the destination spacecraft by single-hop or multi-hops. In addition, if one spacecraft fails, it will not affect the operation of the whole network, which means the survivability of the network arises.

PCF is based on a centralized polling protocol where a point coordinator controls the access to the radio resource. Data sub-network adopts Point to Multi-Point (PMP) structure and works in PCF mode. Each spacecraft can upload payload data to the central module via allocated transmission channel. Specifically, the load spacecraft are responsible for collecting observing data, and the central spacecraft is in charge of processing data from other spacecraft and communicating with the control center.

In order to build flexible DSC network and to avoid complex systems or heavy equipment, we need to optimize MANET protocol stack, as shown in Fig. 2. Control sub-network adopts DCF mode, and data sub-network adopts PCF mode. The function of the heterogeneous sub-network management model is to maintain users' information obtained through control sub-network, including position, velocity and so on. Then by analyzing the topological location information storied in the heterogeneous sub-network management model, data sub-network could realize high-speed data transmission by digital beamforming.

2 Event-Driven MAC Protocol for Control Sub-network

DCF is the fundamental MAC mechanism of IEEE 802.11x. Besides, DCF uses a basic acknowledgment mechanism for verifying successful transmissions as well as an optional RTS/CTS handshaking mechanism for decreasing overhead from collisions. In both cases a binary exponential back-off mechanism is used. Where the back-off time is slotted and the number of back-off slots is randomly chosen in the range [*0, CW*]. At the first transmission attempt, the contention window *CW* is set to the minimum contention window CW_{min}. After several unsuccessful transmissions, CW is finally doubled up to the maximum value $CW_{\max} = 2^m CW_{\min}$. Once CW reaches CW_{max}, it will remain unchanged until the packet is transmitted successfully or the retransmission time reaches the retry limit r. Once the retry limit is reached, the packet will be discarded.

2.1 Description of E-MAC Protocol in Control Sub-network

In control sub-network of DSC, two kinds of spacecraft need to transmit packets with different access strategies. The primary spacecraft follow IEEE 802.11× to contend for the channel as usual. However, the secondary spacecraft make their contention window larger than that of the primary spacecraft in order to defer its transmission after the emergency ones.

Let i represent the types of spacecraft, and i = 1 for primary spacecraft, i = 2 for the secondary spacecraft. According to IEEE 802.11x, the contention window is defined as:

$$W_{i,j} = \begin{cases} CW_{i,\min} & j = 0 \\ 2CW_{i,j-1} & 0 < \mathrm{j} < \mathrm{m}\,. \\ CW_{i,m} & \mathrm{m} \leq \mathrm{j} < \mathrm{r} \end{cases} \tag{1}$$

where j denotes back-off stage, m denotes the maximum back-off stage. The current value of the back-off slot can be obtained as:

$$Backoff_{i,j} = rand\left(0, W_{i,j}\right) + x. \tag{2}$$

where x means an additional variable to distinguish different priorities. For the primary events, x equals zero, otherwise probabilities should be optimized to improve the spectrum and energy efficiency.

2.2 Analytical Model of E-MAC Protocol

Let's consider the contention procedure of a given event of the i-th priority. The tri-dimensional Markov chain in [4, 5] of the back-off process can be represented by (i, s(t), b(t)), where i represents the priority, s(t) stands for the back-off stage and b(t) denotes the back-off count value. In this Markov chain, two special states are added: one is the idle state, which means the MAC queue is empty, and the other is D state, which means the medium is sensed to be idle for a time interval greater than DIFS. A spacecraft can send a packet only at state *(i, j, 0)* or D state.

Let $d_{i,0}$ be the probability that the MAC queue is empty, let $P_{i,b}$ be the probability that the given slot is busy, and let $P_{i,c}$ be the collision probability when the given slot is busy. Define $W_{i,0} = W_{i,min}$ for convenience and adopt $W_{i,j} = 2^j W_{i,0}$.

The transition probabilities from the idle state to idle, D and *(i, 0, k)* state are shown respectively as the following:

$$P(idle|idle) = d_{i,0}. \tag{3}$$

$$P(D|idle) = \left(1 - d_{i,0}\right)\left(1 - p_{i,b}\right). \tag{4}$$

$$P((i,0,k)|idle) = \left(1 - d_{i,0}\right)p_{i,b}/W_{i,0},\ \mathrm{x} \le \mathrm{k} \le \mathrm{W}_{i,0} + x - 1. \tag{5}$$

The transition probabilities from the D state to idle and *(i, 0, k)* states are respectively:

$$P(idle|idle) = d_{i,0}\left(1 - p_{i,c}\right). \tag{6}$$

$$P((i,0,k)|D) = \left[p_{i,c} + \left(1 - p_{i,c}\right)\left(1 - d_{i,0}\right)\right]/W_{i,0},\ \mathrm{x} \le \mathrm{k} \le \mathrm{W}_{i,0} + x - 1. \tag{7}$$

Based on the fact that the sum of the steady-state probabilities of all states must be equal to 1, we can get

$$1 = b_{i,0} + b_{i,D} + \sum_{j=0}^{r}\left(\sum_{k=0}^{W_{i,j}+x-1} b_{i,j,k}\right). \tag{8}$$

By obtaining $b_{i,0,0}$, we can express the probability τ that a satellite transmits in a randomly chosen slot time. As a satellite can send a packet only at *(i, j, 0)* or D state, then

$$\tau_i = b_{i,D} + \sum_{j=0}^{r} b_{i,j,0}. \tag{9}$$

Consider a fixed number n of contending spacecraft, therefore n = n_1 + n_2. The probability that at least one i-th urgency event is transmitted in a given time slot can be derived as follows

$$P_{tr,i} = 1 - (1 - \tau_i)^{n_i}. \tag{10}$$

The probability that exactly one i-th urgency spacegraft generates packets on the channel (assuming that at least one i-th urgency event will happen), can be expressed as

$$P_{s,i} = \frac{n_i\tau_i(1 - \tau_i)^{n_i - 1}\prod_{h=1,h\neq i}^{2}(1 - \tau_h)^{n_h}}{P_{tr,i}}. \tag{11}$$

As regards to the status of packet transmission in a given time slot, there are three possibilities. Firstly, there may be no transmission with the probability of $P_{idle} = (1 - \tau_1)^{n_1}(1 - \tau_2)^{n_2}$, whose average time is σ = *aSlotTime*. Hence the average consumed energy is $E_i = nW_{Rx}\sigma$. Secondly, it contains a successful transmission. The probability that an i-th urgency spacecraft transmits successfully is $P_{tr,i}P_{s,i}$, whose average time is T_s. In the basic acknowledgement mechanism, $T_s = F_i + SIFS + 2\sigma + ACK + DIFS$, where F_i is the average time length of the i-th priority data frame. And then the average consumed energy is $E_s = (W_{Tx} + W_{Rx} + (n - 2)W_{Lx})T_s$. Finally, there may be collision with the probability of $P_c = 1 - P_{idle} - P_{tr,1}P_{s,1} - P_{tr,2}P_{s,2}$, whose average time is $T_c = F^* + DIFS + \sigma$, where F^*, the average length of the longest frame involved in the collision, was discussed in detail in [4]. The average consumed energy is

$$E_c = \sum C_n^c \tau_i^c (1 - \tau_i)^{n-n_c} (n_c W_{Tx} + (n - n_c) W_{Rx}) T_c. \tag{12}$$

Let the average bit size of payloads in the i-th urgency be B_i. Thus, the system spectrum efficiency $\eta_{spectrum}$ and energy efficiency η_{energy} can be expressed respectively as

$$\eta_{spectrum} = \frac{\sum_{i=1}^{2} P_{tr,i} P_{s,i} B_i}{\left(P_e \sigma + \sum_{i=1}^{2} P_{tr,i} P_{s,i} T_s + P_c T_c \right)}. \tag{13}$$

$$\eta_{energy} = \frac{\sum_{i=1}^{2} P_{tr,i} P_{s,i} B_i}{\left(P_e E_i + \sum_{i=1}^{2} P_{tr,i} P_{s,i} E_s + P_c E_c \right)}. \tag{14}$$

2.3 Spectrum and Energy Efficiency of E-MAC Protocol

From the analysis in the previous subsections, we present the event-driven MAC protocol, E-MAC, to improve the viability of DSC by adjusting the contention parameters according to the number of spacecraft in emergent circumstances and normal flights respectively. From equations above, we can explicitly compute the optimal values of x to guarantee the QoS of emergent spacecraft which has higher priority. The relationship between x and energy efficiency as well as the relationship between x and spectrum efficiency is shown in Fig. 3. As we can see, along with the increasing of x, the peak of the energy efficiency and that of the spectrum efficiency are not at the same x, but we can find a relatively optimum x, at which the energy efficiency and spectrum efficiency can be both at a relatively high level.

We can get a range of x, between which the spectrum efficiency is not smaller than Q time of the maximum of the spectrum efficiency and the energy efficiency is not smaller than Q time of the maximum energy efficiency. Here we choose Q as 99.8%. For instance, [$x_{1,min}$, $x_{1,max}$] satisfies the required spectrum efficiency, and [$x_{2,min}$, $x_{2,max}$] satisfies the required energy efficiency. Then choose a value in the intersection of [$x_{1,min}$, $x_{1,max}$] and [$x_{2,min}$, $x_{2,max}$], i.e. satisfying the below formulation:

$$x \in \left[x_{1,\min}, x_{1,\max}\right] \cap \left[x_{2,\min}, x_{2,\max}\right]. \tag{15}$$

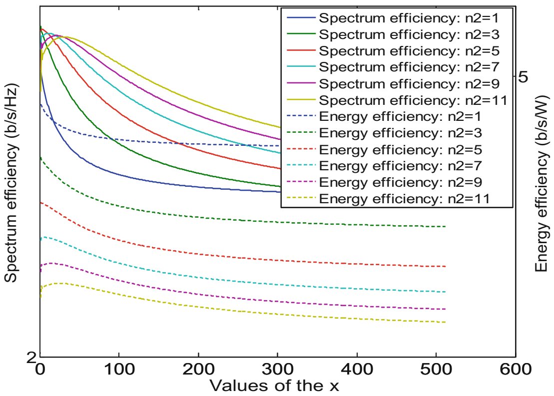

Fig. 3. Energy and spectrum efficiency versus x.

3 Performance Evaluation

In order to evaluate the proposed E-MAC protocol, the following simulations are made in OPNET. In the simulations, we consider two different scenarios.

3.1 Scenario I

Consider a rectangular area of 30 km × 30 km × 30 km with 20 spacecraft shown in Fig. 4 (left). For comparison, we consider two network architectures, one is the proposed heterogeneous control and data split network, and the other is the traditional network, where both control and data packets are tightly coupled to transmit over the IEEE 802.11x-based system [3]. The main parameters of the simulation are shown in Table 1.

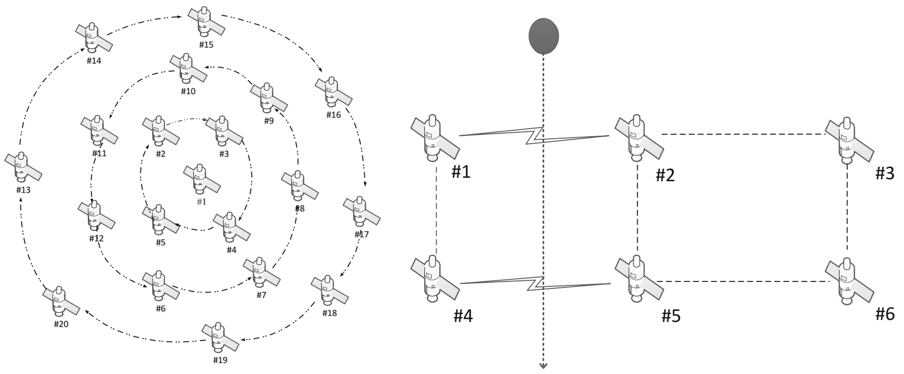

Fig. 4. Network topology for scenario I (left) and scenario II (right).

Table 1. Simulation parameters.

Parameters	Control sub-network	Data sub-network	Traditional network
Carrier frequency	2431 MHz	2401 MHz	2401 MHz
bandwidth	11 MHz	11 MHz	22 MHz
Data rate	1Mbps	11Mbps	11Mbps
Transmit power	0.4 W	0.4 W	0.4 W
Antenna mode	Omnidirectional	Directional	Omnidirectional
Access method	DCF	PCF	DCF (default)/PCF (optional)

As is shown in Fig. 5, compared with [3], the throughput of proposed network is slightly improved. And along with the improving of network load, the throughput of the proposed network continues to grow but that of the traditional slightly decreases. As to delay, the proposed network structure has a better delay property, and with the network load increasing, the performance of the proposed network has more advantage than that of the traditional network.

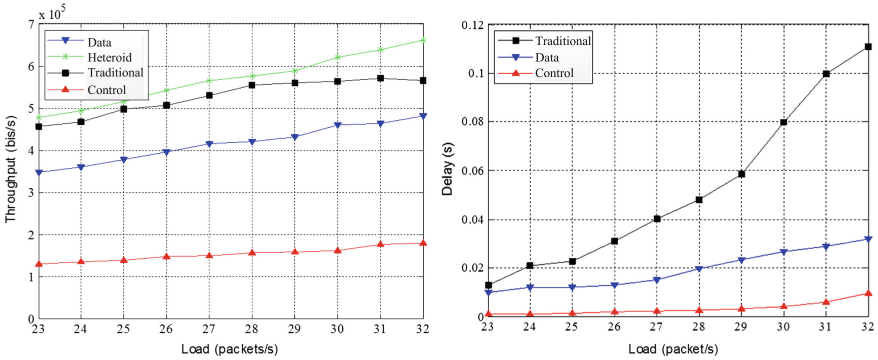

Fig. 5. Throughput (left) and delay (right) properties in diverse loads.

In Fig. 6, it is obvious that the proposed network, which is an overall index, has larger transmission efficiency than general network.

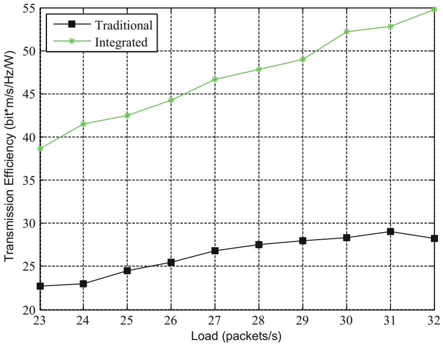

Fig. 6. Transmission efficiency property in diverse loads.

3.2 Scenario II

For simplicity, we consider a PFF with 6 spacecraft, of which the relative speed is 30 km/h, and an obstacle, which could be a space junk or a small meteorite, flies through the formation, just as shown in Fig. 4 (right). The orbits of the micro-satellite #1, #2, #4, #5 are influenced by the obstacle, so they would become the primary spacecraft according to the proposed E-MAC protocol.

As shown in Fig. 7, the average delay of primary spacecraft is about 8 ms, a bit lower than that of the secondary spacecraft (around 1.35 ms on average). As the primary spacecraft have a shorter back-off time, and the collision probability can be significantly reduced, so the emergency messages can be transmitted timely.

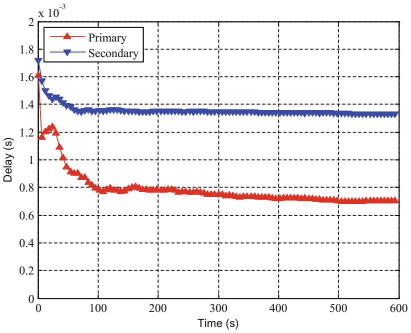

Fig. 7. Average delay of the primary and secondary spacecraft in control sub-network.

Figure 8 compares the energy and spectrum efficiency between CSMA/CA and the proposed E-MAC protocol. Obviously, spectrum efficiency in the proposed protocol is almost equal to CSMA/CA, at around 0.0117 bit/s/Hz. Besides, the energy efficiency of the proposed protocol is also close to that of CSMA/CA, fluctuating between 0.028 and 0.031 bit/s/Hz/W. Both indicate that the proposed protocol can reduce the collision of the DSC system effectively without obvious deterioration of energy consumption.

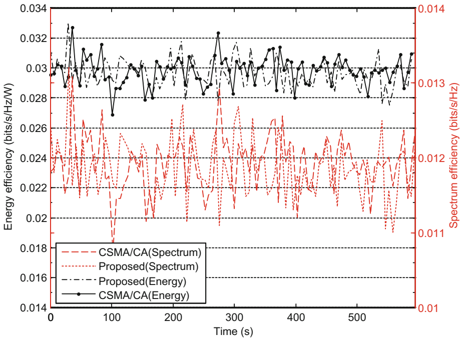

Fig. 8. Energy and spectrum efficiency of control sub-network.

4 Conclusion

In this paper, a heterogeneous network architecture using E-MAC protocol is proposed for PFF-based DSS. Two sub-networks can transmit control messages and data messages in DCF and PCF mode respectively. Then, we propose event-driven MAC protocol for control sub-network, which enables the DSC to response to the triggering events and guarantee the QoS of the control sub-network. Simulation results demonstrate that the proposed network structure can achieve better overall performance.

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