A Dynamic Channel Access Strategy for Satellite Networks Supporting Service Priority Postprint

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Abstract

To address the issue where services of remote combat aircraft accessing satellite channels exhibit priority levels, and the burstiness of high-priority services impacts channel utilization and throughput, a dynamic channel access strategy for satellite networks supporting service priorities is proposed. This strategy employs cognitive radio technology to construct a spectrum pool for channel sharing, enables transparent channel access for high-priority services while reserving channels to guarantee successful access for low-priority services, and utilizes a queuing model for services awaiting channel access. Simulation results indicate that the proposed strategy efficiently ensures the success rate of high-priority service channel access and effectively reduces access delay; furthermore, it significantly mitigates the impact of high-priority service burstiness on low-priority service access, enhances the comprehensive utilization of satellite channels, decreases low-priority service access delay, and ensures the throughput efficiency of low-priority services accessing the satellite network.

Full Text

Dynamic Channel Access Strategy Supporting Service Priority for Satellite Communication Networks

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Abstract

To address the problem of low channel utilization and throughput caused by the burstiness of high-priority traffic when long-range combat aircraft access satellite channels with differentiated priority services, this paper proposes a dynamic channel access strategy supporting service priority for satellite communication networks. The strategy introduces cognitive radio technology to construct a spectrum pool for channel sharing, enabling transparent access for high-priority services while reserving channels to guarantee successful access for low-priority services. Services that cannot access channels immediately employ a queuing model to wait for access. Simulation results demonstrate that this strategy can effectively guarantee the success rate of high-priority service channel access while reducing access delay. It also mitigates the impact of high-priority service burstiness on low-priority service access, improves the comprehensive utilization of satellite channels, reduces low-priority service access delay, and ensures the throughput efficiency of low-priority services accessing the satellite network.

Key Words: satellite network; channel access; priority; Markov process; queuing theory

0 Introduction

As national interest protection requirements continue to strengthen and operational ranges expand, long-range operations by fighter aircraft, bombers, and early warning platforms have become essential operational patterns. These platforms have substantial demands for real-time battlefield information distribution and efficient, accurate transmission of combat commands. Traditional ground wireless networks with limited coverage can no longer satisfy operational requirements, making reliance on satellite communication systems for information support imperative.

Channel access strategy is one of the key technologies in satellite networks, significantly impacting network reliability, throughput, and other performance metrics. Therefore, establishing an efficient, fast, stable, and low-blocking access strategy is of great importance. Reference [2] proposes an RRDAMA-P access protocol combining prioritized random reservation/on-demand phase division, which effectively guarantees delay performance for high-priority nodes but provides limited improvement in low-collision and low-channel-switching performance for low-priority services. Reference [3] introduces an APRMA mechanism that adaptively accesses channels based on channel load and service QoS requirements, improving comprehensive network resource utilization for different service types. However, this mechanism introduces high system overhead and fails to adequately consider different service priority requirements, only providing QoS differentiation for different service types without distinguishing access priority levels. Reference [4] presents a random backoff strategy for MAC layer channel access during PTT service contention, which better ensures the contention success rate for high-priority service users during conflicts but offers limited improvement in reducing conflicts, increasing low-priority user access success rates, and enhancing overall network throughput. Reference [5] proposes a hybrid channel access method combining random access and on-demand allocation, which improves overall system throughput. However, the channel access strategy only differentiates services based on bandwidth requirements, resulting in insignificant reduction in data collision rates during random access, and the strategy design is based on ideal assumptions with high requirements for threshold setting and selection.

To address these issues, and building upon analyses in references [1,6-8] that demonstrate cognitive radio technology can effectively improve network channel utilization, reduce collision probability, and enhance network throughput when applied to satellite networks, this paper introduces cognitive radio technology and draws on the spectrum pool concept to propose a dynamic channel access strategy supporting service priority for satellite networks. This strategy can effectively guarantee the success rate of high-priority service channel access while minimizing the impact of high-priority service burstiness on low-priority service transmission, thereby improving satellite network channel utilization and ensuring low-priority service network throughput.

1 System Model

Long-range combat aircraft platforms require satellite communication network support during extended-range, cross-regional operations. In the network model shown in [Figure 1: see original paper], large aerial backbone platforms (such as early warning aircraft) in different regions operate beyond line-of-sight ranges, as do their affiliated small combat units. Small flight platforms can directly access the satellite network or achieve long-distance, cross-domain communication by first accessing large flight platforms. Multiple types of flight platforms can access the satellite network to achieve beyond-line-of-sight communication, and the transmitted services are diverse.

Different flight user platforms (such as fighter aircraft) can transmit different types of services in different time slots. The platforms themselves do not have priority differentiation; they only classify services into different priorities based on operational mission requirements. Services can be divided into two categories: high-priority traffic (HPT) and low-priority traffic (LPT). High-priority traffic includes command messages and short voice services directly related to combat commands, while low-priority traffic includes situational information indirectly related to combat commands. Due to battlefield environments and combat communication command requirements, high-priority traffic exhibits burstiness compared to low-priority traffic. Therefore, the designed access strategy should ensure efficient and accurate access for high-priority services while minimizing impact on low-priority service channel access.

2 Access Strategy Analysis

2.1 Problem Assumptions

To simplify the analysis of user access to satellite channels while maintaining generality, the following assumptions are made:

a) Each user’ s priority in accessing the satellite network is consistent with the priority of the transmitted service. At any given moment, a user can only transmit one type of priority service, and the user’ s priority changes with the type of service being transmitted.

b) Cognitive radio technology is introduced in all flight user platforms, each possessing perfect cognitive capability to effectively sense idle spectrum in the satellite network not occupied by high-priority users.

c) When a user transmitting low-priority traffic detects high-priority service transmission in the channel, the low-priority service enters a waiting queue until the user detects idle spectrum again.

d) Services transmitted when users access satellite channels do not interfere with each other, and users of each priority can only use a single frequency band to transmit data.

2.2 Access Strategy Design

The satellite communication network has n equal-width channels available to users. Due to mission requirements, high-priority services such as command messages and short voice services have relatively low transmission frequency. To improve low-priority service transmission efficiency while guaranteeing high-priority service transmission, and to enhance channel resource utilization in bandwidth-constrained satellite communication networks, this paper draws on the spectrum pool concept from cognitive radio technology to achieve channel resource sharing.

Based on two users competing to access the satellite communication network using multi-channel ALOHA, the strategy reserves an appropriate number of channels for high-priority users to guarantee high-priority service transmission. The number of reserved channels is m $(m < n)$. High-priority users access channels sequentially from c_1 to c_n according to channel numbers, prioritizing idle reserved channels with smaller numbers. When all m reserved channels are occupied, they select an idle channel from the $n - m$ non-reserved channels in ascending order. The high-priority traffic transmission system is modeled as an M/M/n queuing system, while the low-priority traffic transmission system is modeled as a preemptive priority M/M/(n-m) queuing system [9]. Thus, low-priority users can access at most $n - m$ channels.

Users transmitting different priority services cannot access the same channel simultaneously. This access strategy can be represented by the access model shown in [Figure 2: see original paper]. In this model, high-priority users can access any channel—low-priority users’ channel occupancy is completely transparent to high-priority users. However, to ensure low blocking rates and low channel switching rates for low-priority users, high-priority users prioritize accessing reserved idle channels and can only occupy low-priority users’ channels when all reserved channels are occupied. Low-priority users can only select remaining idle channels after sensing spectrum holes [10]. Both high-priority traffic with large data volumes and other low-priority traffic use appropriate queuing models to wait in corresponding high-priority or low-priority queues for idle channels.

3 Markov Model

3.1 Problem Analysis

The arrival of high-priority services accessing the satellite network follows a Poisson distribution with parameter λ_H, while low-priority service arrival follows a Poisson distribution with parameter λ_L. The service time for high-priority services follows a negative exponential distribution with parameter μ_H, and the service time for low-priority services follows a negative exponential distribution with parameter μ_L.

Since all available channel resources are transparent to high-priority services during channel access, we define the forced disconnection state for low-priority services as occurring when a channel occupied by low-priority service is preempted by high-priority service, causing current access failure. The access blocking state for low-priority services occurs when all channels accessible to low-priority services are fully occupied by either high-priority or low-priority services. When low-priority services access the satellite network, the resulting disconnection rate is P_{fdrop} and the access blocking rate is P_{block}.

To represent the states and possible state transitions when different priority services access channels, this paper introduces a Markov model [11] to illustrate the states of different priority services accessing the spectrum pool.

3.2 Markov Model Establishment

Based on the proposed access strategy, the access states of different priority services needing to access the satellite network can be divided into three types: collision-free access state, forced disconnection state, and access blocking state [12]. This establishes the Markov model shown in [Figure 3: see original paper].

In the Markov model, any state is represented by (i, j, k), where i and j denote the number of users waiting to access the satellite network transmitting high-priority and low-priority services respectively, and k represents the access state to the satellite network. $k = 0, 1, 2$ respectively indicate collision-free access state, forced disconnection state, and access blocking state.

3.3 Steady-State Equations

According to Markov process theory, defining $P(i, j, k)$ as the steady-state probability, we can establish the corresponding steady-state equations for the Markov process in [Figure 3: see original paper] by category.

When $j = 0$, $0 \leq i < n - m$, and $k = 0$:

$$(0, j, 0) = \frac{[\lambda_L + j\mu_L]P(0, j, 0) + \lambda_H P(1, j, 0) + (j + 1)\mu_L P(0, j + 1, 0)}{\lambda_H + \lambda_L + j\mu_L + \mu_H \delta_{j0}}$$

where $\delta_{j0} = \begin{cases} 1 & j = 0 \\ 0 & j \neq 0 \end{cases}$

When $i = 0$, $j = n - m$, and $k = 0$:

$$(0, n - m, 0) = \frac{[\lambda_L + (n - m)\mu_L]P(0, n - m, 0) + \lambda_H P(1, n - m, 0) + \lambda_L P(0, n - m, 2)}{(n - m)\mu_L + \lambda_H}$$

When $j = 0$, $0 < i \leq m$, and $k = 0$:

$$(i, 0, 0) = \frac{[\lambda_H + \lambda_L + i\mu_H]P(i, 0, 0) + \lambda_H P(i - 1, 0, 0) + \lambda_L P(i, 1, 0)}{\lambda_H + \lambda_L + i\mu_H + \mu_L}$$

When $0 < j < n - m$, $1 \leq i \leq m$, and $k = 0$:

$$(i, j, 0) = \frac{[\lambda_H + \lambda_L + i\mu_H + j\mu_L]P(i, j, 0) + \lambda_H P(i - 1, j, 0) + \lambda_L P(i, j - 1, 0) + (j + 1)\mu_L P(i, j + 1, 0)}{\lambda_H + \lambda_L + i\mu_H + j\mu_L}$$

When $i = m + 1$, $0 \leq j < n - m$, and $k = 0$:

$$(i, j, 0) = \frac{[\lambda_H + \lambda_L + i\mu_H]P(i, j, 0) + \lambda_L P(i, j - 1, 0) + (i + 1)\mu_H P(i + 1, j, 0) + \lambda_H P(i, j, 2)}{\lambda_H + \lambda_L + i\mu_H}$$

When $i + j = n$, $i \geq m$, and $k = 0$:

$$(i, j, 0) = \frac{[\lambda_H + \lambda_L + i\mu_H + j\mu_L]P(i, j, 0) + \lambda_L P(i, j - 1, 0) + \lambda_H P(i - 1, j, 0)}{\lambda_H + \lambda_L + i\mu_H + j\mu_L}$$

When $1 \leq i \leq m$, $j = n - m$, and $k = 0$:

$$(i, 0, 0) = \frac{[\lambda_H + i\mu_H]P(i, 0, 0) + \lambda_H P(i - 1, 0, 0) + \mu_H P(i + 1, 0, 0) + \lambda_L P(i, 1, 0)}{\lambda_H + i\mu_H + \mu_L}$$

When $1 \leq i \leq m + 1$, $j = n - m - 1$, $1 \leq k < n$, and $i + j = n$:

$$(i, j, 0) = \frac{[\lambda_H + \lambda_L + i\mu_H]P(i, j, 0) + \lambda_L P(i, j - 1, 0) + \lambda_H P(i - 1, j, 0) + \lambda_H P(i, j, 2)}{\lambda_H + \lambda_L + i\mu_H}$$

The disconnection rate and blocking rate for low-priority services accessing the satellite network are:

$$P_{fdrop} = \sum_{i=0}^{n-1} P(i, n - m, 1)$$

$$P_{block} = \sum_{i=0}^{m} \sum_{p=0}^{n-m} P(i + p, n - m, 2)$$

3.4 Optimal Reserved Channel Determination

According to the proposed access strategy, users transmitting high-priority services have transparent access to channels relative to low-priority users [13]. Therefore, users transmitting high-priority services can achieve maximum capacity transmission when accessing satellite channels. The maximum capacity V for low-priority users accessing channels is achieved when low-priority service transmission reaches maximum capacity.

The optimal number of reserved channels m is determined by:

$$m = \arg \max_{0<m<n} \{\min\{\lambda_L^{block}, \lambda_L^{fdrop}\}\}$$

where λ_L^{block} and λ_L^{fdrop} represent the low-priority service arrival rates that satisfy the blocking rate and disconnection rate constraints, respectively. Thus, the optimal reserved channel number is the number that achieves maximum low-priority user channel access capacity.

4 Performance Metrics Analysis

The direct impact of successful access for high-priority and low-priority services is primarily reflected in increased transmission delay and decreased channel throughput and rate. This paper selects service transmission delay, throughput rate, and throughput as evaluation metrics.

4.1 Delay Performance Analysis

Transmission delay is a critical reference indicator for measuring the quality of service performance of satellite networks for different priority services. Since high-priority services are unconstrained when accessing channels, the channel is effectively transparent to them. Therefore, the delay for high-priority services is slightly lower than that for low-priority services.

The delay primarily consists of data transmission delay in wireless channels and queuing waiting delay. Since reserved channels can only be accessed by high-priority services, we classify different priority service access scenarios.

4.1.1 High-Priority Service Access Delay In the Markov process, when high-priority services access the satellite network, whether the channel is occupied by low-priority services is transparent to them. High-priority services only need to queue when channels are occupied by other high-priority services; all other cases allow direct access. Therefore, the delay for high-priority services accessing satellite channels (i.e., the average queuing waiting time for high-priority services, including queuing time and service time) can be equivalent to an M/M/n queuing system with only one customer type waiting for service. The delay for high-priority services accessing satellite channels [15] is:

$$t_{del}^{H} = \frac{1}{\mu_H} + \frac{P_0 \rho_1^n}{n! \cdot n\mu_H (1-\rho_1)^2}$$

where P_0 represents the steady-state distribution of the M/M/n queuing system:

$$P_0 = \left[\sum_{k=0}^{n-1} \frac{\rho_1^k}{k!} + \frac{\rho_1^n}{n!(1-\rho_1)} \right]^{-1}$$

and $\rho_1 = \frac{\lambda_H + \lambda_L}{n\mu_H}$.

4.1.2 Low-Priority Service Access Delay Low-priority services can use any of the $n-m$ idle channels not occupied by high-priority services. Therefore, for low-priority services, the channel access model can be established as a preemptive priority M/M/(n-m) queuing system, where newly arrived high-priority services without reserved channel access preempt channels from low-priority services to ensure their own access.

The $n-m$ idle channels in the satellite network are equivalent to $n-m$ servers in the queuing model. All high-priority and low-priority services are customers waiting for service, with high-priority services having the highest channel access priority. According to the queuing model, the delay for low-priority services accessing the satellite network (i.e., the average sojourn time, consisting of queuing time and service time) is:

$$t_{Del}^{L} = \frac{1}{\mu_L} + \frac{P_s \rho_2^{n-m}}{(n-m)! \cdot (n-m)\mu_L (1-\rho_2)^2} \cdot \frac{\lambda_H}{\mu_H}$$

where P_s represents the steady-state distribution of the M/M/(n-m) queuing system:

$$P_s = \left[\sum_{k=0}^{n-m-1} \frac{\rho_2^k}{k!} + \frac{\rho_2^{n-m}}{(n-m)!(1-\rho_2)} \right]^{-1}$$

and $\rho_2 = \frac{\lambda_H + \lambda_L}{(n-m)\mu_L}$.

4.2 Throughput Performance Analysis

In the designed dynamic channel access strategy, high-priority services have transparent access to satellite channels. Since high-priority services are mostly bursty data or voice services with low throughput performance requirements, throughput performance has minimal impact on them. As long as unoccupied channels exist, arriving high-priority services can achieve maximum channel access guarantee. Therefore, this analysis focuses on low-priority service throughput when accessing channels.

Based on input/output balance, throughput is an important indicator for comparing the access efficiency of different strategies. Network throughput represents the number of different priority services successfully accessing the satellite network per unit time. The data throughput Th expression is:

$$Th = \lambda_L(1 - P_{block})(1 - P_{fdrop})\mu_L$$

5 Simulation Results

5.1 Impact of Different Priority Service Arrival Rates on Network Access Performance

To compare how different priority service arrival rates affect low-priority service access performance and determine the optimal number of reserved channels, while considering computational complexity, this paper selects a total channel count $n = 4$ and compares the relationship between blocking probability and forced disconnection rate with different priority service arrival rates when the reserved channel count m is 0, 1, and 2.

5.1.1 Impact of High-Priority Service Arrival Rate on Network Access Performance The simulation selects low-priority service arrival rate $\lambda_L = 0.3$, service rate $\mu_L = 0.6$, and high-priority service rate $\mu_H = 0.4$. The results showing the impact of high-priority service arrival rate on low-priority service access performance are presented in [Figure 4: see original paper].

The simulation results in [Figure 4: see original paper] show that under different reserved channel constraints, as the high-priority service arrival rate increases, both the forced disconnection rate and blocking probability for low-priority services continuously increase. This occurs because increasing high-priority service arrival rates occupy non-reserved channels, causing low-priority services accessing channels to be preempted.

When the reserved channel number is 2 and the high-priority service arrival rate is high, high-priority service access to the satellite network produces a lower disconnection rate for low-priority services, but the blocking probability increases significantly compared to other reserved channel configurations. When the reserved channel number is 1, both the access blocking rate and disconnection rate decrease compared to no reservation. This is because with one reserved channel, the randomness of high-priority service arrival has minimal impact on low-priority service access, while non-reserved channels can better satisfy low-priority service channel access requirements, resulting in lower blocking and forced disconnection rates.

5.1.2 Impact of Low-Priority Service Arrival Rate on Network Access Performance The simulation selects high-priority service arrival rate $\lambda_H = 0.4$, service rate $\mu_H = 0.4$, and low-priority service rate $\mu_L = 0.6$. The relationship between low-priority service arrival rate and its access performance is shown in [Figure 5: see original paper].

The results in [Figure 5: see original paper] indicate that as the low-priority service arrival rate increases, the blocking probability growth rate continuously rises while the disconnection probability increases slowly. When the reserved channel number increases, the blocking rate for low-priority services accessing satellite network channels continuously increases, while the disconnection rate continuously decreases. This is because with a stable high-priority service arrival rate, the increasing low-priority service arrival rate causes newly arrived low-priority services to be blocked. However, since the high-priority service arrival rate remains stable, it does not cause low-priority service disconnection by occupying non-reserved channels. As the number of reserved channels increases, the impact of high-priority service arrival on low-priority services currently accessing satellite channels continuously decreases, thereby reducing the disconnection rate. Meanwhile, the number of channels accessible to low-priority services continuously decreases, increasing the blocking probability.

5.1.3 Determination of Optimal Reserved Channel Number To determine the optimal reserved channel number, the simulation sets the allowed blocking rate threshold for low-priority services at 0.03 and the forced disconnection rate threshold at 0.02. This allows determination of the maximum low-priority service arrival rate permitted under different reserved channel constraints.

[Figure 6: see original paper] shows the relationship between different reserved channel numbers and the maximum allowed low-priority service arrival rate. Based on the simulation results from [Figure 4: see original paper] and [Figure 5: see original paper], when the total channel number is 4, different reserved channels satisfy the system blocking rate and forced disconnection rate threshold requirements to achieve maximum capacity for low-priority users accessing satellite channels. Clearly, when the total channel number is 4, selecting a reserved channel number of 1 ensures that high-priority services access the satellite network with maximum data volume while producing minimal forced disconnection and blocking probabilities for low-priority services. Thus, both service types can achieve efficient access, effectively guaranteeing the overall system service rate.

5.2 Performance Comparison of Different Access Strategies

Based on the analysis in Section 4.1, when the total channel number $n = 4$ and the reserved channel number $m = 1$, high-priority services can access efficiently while achieving low blocking and forced disconnection rates for low-priority services. The simulation sets high-priority service arrival rate $\lambda_H = 0.4$, service rate $\mu_H = 0.5$, and low-priority service rate $\mu_L = 0.6$ when low-priority service arrival rate varies. When high-priority service arrival rate varies, low-priority service arrival rate $\lambda_L = 0.3$, service rate $\mu_L = 0.6$, and high-priority service rate $\mu_H = 0.4$. The delay performance comparison among different access strategies is shown in [Figure 7: see original paper].

The results in [Figure 7: see original paper] demonstrate that the proposed dynamic satellite channel access strategy achieves lower access delay compared to both ALOHA random contention access and CSMA-CD access methods. This is because the dynamic access strategy introduces cognitive radio technology to ensure accurate sensing of idle spectrum, and the established spectrum pool enables efficient spectrum resource sharing. Channel reservation effectively guarantees high-priority service access while enabling low-priority service channel access, thereby ensuring low-delay characteristics for both service types. However, since high-priority service access is transparent relative to low-priority services, high-priority service access delay is slightly lower than that of low-priority services.

Setting high-priority service arrival rate $\lambda_H = 0.6$, service rate $\mu_H = 0.4$, and low-priority service rate $\mu_L = 0.8$, the relationship between low-priority service arrival rate and throughput under different access strategies is compared, with results shown in [Figure 8: see original paper].

The results in [Figure 8: see original paper] show that when low-priority service arrival rate increases, throughput first increases then slowly decreases with ALOHA contention access, continuously increases with CSMA-CD access, and continuously increases with the proposed strategy while showing slight improvement over CSMA-CD. This is because the proposed strategy effectively guarantees transparent access for high-priority services while introducing cognitive radio for effective spectrum sensing and sharing, achieving minimum collision probability and maximum channel resource utilization. This ensures maximum throughput for high-priority service access while reducing the impact of high-priority service burstiness on low-priority service access through reserved channel resources, thereby achieving higher throughput for low-priority services accessing satellite channels.

6 Conclusion

This paper addresses the problem of prioritized services with burstiness affecting channel occupancy and throughput when long-range combat aircraft access satellite channels. Drawing on cognitive radio technology, it proposes a dynamic channel access strategy supporting service priority for satellite networks. The strategy enables transparent access for high-priority services while reserving channels to guarantee low blocking and disconnection rates for low-priority services, with non-accessing services using queuing models to wait for access. This strategy can effectively guarantee the success rate of high-priority service channel access while minimizing the impact of high-priority service burstiness on low-priority service transmission, thereby improving satellite network channel utilization and ensuring low-priority service throughput efficiency.

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Note: Figure translations are in progress. See original paper for figures.