A Practical Joint Coding-Modulation Mode and Frequency-Time Resource Allocation Approach in MF-TDMA Satellite Communication Systems

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Abstract. In general, the problem of the resource management in the MF-TDMA satellite communication system can be divided into two phases: a timeslot calculation phase for each connection request and a timeslot allocation phase in the frame structure. In this paper, we propose algorithms to solve this two-phases problem. In the former phase, we first allocate each connection request on an appropriate carrier based on the traffic demand of each connection request, and next dynamically adjust the coding and modulation mode of each connection request, according to the channel condition and state of the system resource usage. Then we calculate the number of timeslots required to be assigned to each connection request. In the latter phase, we propose an algorithm called Best Fit (BF)-modified to allocate the timeslots in the MF-TDMA frame structure. Simulation results show that although the total traffic demands generated by all the connection requests are various, the timeslot is sufficiently utilized due to the dynamical adjustment of the coding and modulation mode. Moreover, the performance of the proposed (BF)-modified algorithm is better than that of the existing algorithm.

Keywords: MF-TDMA satellite communication system · Resource management · Dynamic coding and modulation adjustment · BF-modified algorithm

1 Introduction

The multi-frequency time division multiple access (MF-TDMA) technique is an efficient multiple access technique, since it has the most desirable feature of both the FDMA and TDMA technique [1]. Thus the technique has been employed in many satellite systems, such as EHF-SATCOM, IP-Star, DVB-RCS system and so on.

Figure 1 shows the configuration of the MF-TDMA satellite communication system. There are several terminals and one Network Control Center (NCC) in the system, and each terminal provides service to multiple connections, such as telephone, fax, IP data and so on. In this paper, the transponder in the satellite is assumed to be transparent.

Q. Wu et al. (Eds.): WiSATS 2020, LNICST 358, pp. 282–296, 2021.
https://doi.org/10.1007/978-3-030-69072-4_24

Thus MF-TDMA is employed as the access method for both the uplink and downlink. In addition, the terminal in the system supports multiple coding and modulation modes. In every frame, the terminals send connection requests to the NCC via the satellite, and then the NCC generates terminal burst time plan (TBTP) table and sends it to terminals. Upon receiving the TBTP table, each terminal reads the TBTP table to know what timeslots are assigned.

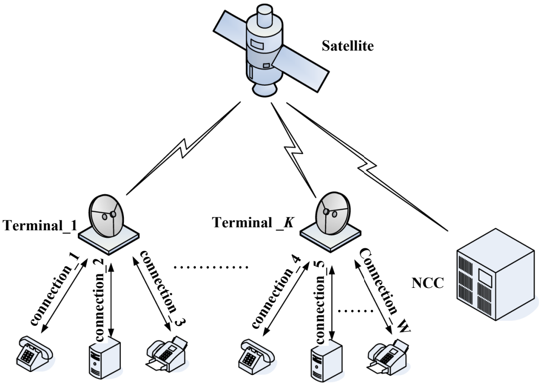

Fig. 1. Configuration of the MF-TDMA satellite system.

Figure 2 shows the frame structure of the MF-TDMA satellite communication systems. The frame is divided into carriers in term of the frequency, and each carrier is divided into timeslots in term of the time. Each timeslot consists of header, traffic and tail. The header consists of several symbols, which are used for bit synchronization. The tail is a period of free time, which is used for timeslot protection. The traffic is the time in which the terminal sends information. The length of each timeslot in different carrier is same or different, and different timeslots can adopt different coding and modulation modes. Thus it is flexible for us to manage the resource. However, it is the flexibility that introduces great difficulty to find the optimal solution for the resource management. To this end, in this paper we aim to find a considerable feasible solution to the problem.

In the practical MF-TDMA satellite communication system, the manager allocates each connection request in the appropriate carrier and timeslot, satisfying some basic restrictions given as follows [2, 3]:

1. A single terminal cannot be assigned more than the total timeslots in a carrier (It is supposed that only one transmitting and receiving system in each terminal).
2. A slot can't be assigned to multi-users.
3. The set of timeslots used by a terminal must be in the same carrier.
4. The set of timeslots used by a terminal to support a given single connection must be contiguous in one carrier.
5. A terminal can't use timeslots in different carriers that overlap in time.

The restriction 1 and 2 are easy to understand. The restriction 3 is imposed to simplify transmitting in the terminal, when the terminal can't hop from one carrier to another

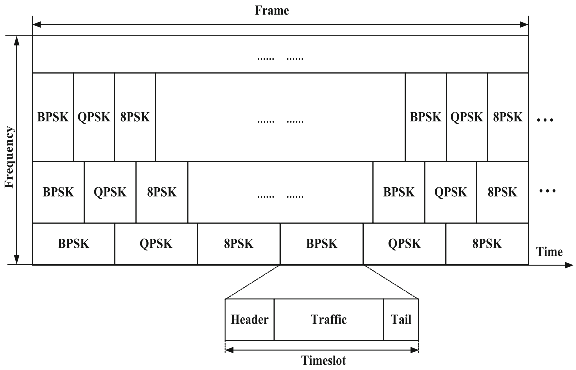

Fig. 2. MF-TDMA channel structure.

carrier fast. The restriction 4 recommended by the DVB-RCS [4] is set to reduce the computational complexity of the resource management. The restriction 5 is imposed to avoid intermodulation products when multiple carriers are present in one terminal at the same time. The restriction 5 is illustrated in Fig. 3.

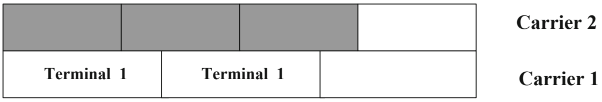

Fig. 3. An example of restriction 5.

As shown in Fig. 3, one connection from terminal 1 has occupied two timeslots in carrier 1, due to the restriction 5, the shadow timeslots in the carrier 2 can't be allocated to other connections from terminal 1, and only the white timeslots can be allocated to them.

Resource management in the MF-TDMA satellite communication system can be divided into two phases: a timeslot calculation phase and a timeslot allocation phase. The former phase calculates the minimum number of timeslots required to provide the desired level of bit error rate (BER) and data rate. The latter phase allocates the actual timeslots in the MF-TDMA frame structure. In the timeslot calculation phase, timeslots required to be assigned to each connection is determined by the modulation and coding mode and carrier symbol rate. In the existing studies [2] and [5], the modulation and coding mode of each connection request is only determined by the channel condition, regardless of state of the system resource usage. Motivated by the cross-layer design [6], we propose an algorithm which dynamically adjusts the modulation and coding mode according to the channel condition of each connection request and state of the system resource usage, taking into account the compromise between the system capacity and the terminal transmitting power. The proposed algorithm guarantees that the timeslot is sufficiently utilized, although the total traffic demands generated by all the connection requests are various. In addition, in the previous literature [2] and [3], the symbol rate of each carrier is assumed to be same. However, the assumption causes some problems.

When there are multiple connection requests from one terminal and the traffic demand of one connection request is high, the connection request will occupy many timeslots in one carrier. As a result, it is difficult to allocate timeslots in another carrier to the rest connection requests from the same terminal, due to the restriction 5. When the traffic demand of one connection request is low, it can't use one timeslot sufficiently and causes waste of the resource. To overcome the drawback mentioned above, in the MF-TDMA satellite communication system we studied in this paper, the symbol rate of each carrier is set to be various. Thus we encounter a new problem that how to choose an appropriate carrier for each connection request. We propose an algorithm to solve this problem.

As the carrier symbol rate and coding and modulation mode are given for each connection request, the timeslots number assigned to it is calculated. Then the next phase of resource management is allocating the timeslots in the frame structure. In [2], an algorithm called Reserve Channel with Priority (RCP)-Fit was proposed. To further improve the performance of RCP-Fit algorithm, the works in [3] proposed an algorithm called RCP-A. The effort of both the RCP-Fit and RCP-A algorithm is to get rid of impact of the restriction 3. However, as the development of the hardware, the restriction 3 can be ignored in the practical system. Thus advantage of the RCP-Fit and RCP-A algorithm is not obvious. To this end, the works in [7] proposed the Convergent Sequential-Fit (CSF) algorithm to reduce the computational complexity. In this paper, we also ignore the restriction 3, and propose a heuristic algorithm called Best Fit (BF)-modified algorithm, which outperforms the CSF algorithm.

The remainder of this paper is organized as follows. Resource management is formulated in the Section 2. The timeslot calculation and timeslot allocation phases are described in Section 3 and Section 4, respectively. Simulation results are provided in the Section 5. Finally, Section 6 concludes the paper.

2 Mathematical Formulation of the Resource Management in the MF-TDMA Satellite System

It is assumed that the MF-TDMA satellite communication system consists of K terminals X_i, $i \in \{1, 2,\ldots, K\}$, and W connections C_i, $i \in \{1, 2,\ldots, W\}$. The set of connections which are served by the terminal X_i is denoted by $\mathcal{N}_i$, and the terminal X_i supports V_i kinds of the coding and modulation mode. The frame consists of N carriers F_i, $i \in \{1, 2,\ldots, N\}$. The symbol rate and timeslot length of the i-th carrier are S_i and L_i, respectively. The length of the timeslot header and tail in the i-th carrier are Hi and T_i, respectively. The length of the frame is T_{frame}. Thus the timeslot number of the i-th carrier Y_i is $\lfloor T_{frame} / L_i \rfloor$, $i \in \{1, 2,\ldots, N\}$.

The traffic demand of the connection C_i is D_i. The coding and modulation mode assigned to the connection C_i is m_i. The bandwidth efficiency of the coding and modulation mode m_i is η_i. For the given bit error rate in the system, the corresponding threshold signal-to-noise ratio (SNR) per bit of the coding and modulation mode m_{ij} is $\left(E_b / n_0\right)_{th}^{i}$. If the connection C_i is assigned on the n-th carrier, it is denoted that $w_n^i = 1$. Otherwise, $w_n^i = 0$. Thus the number of timeslots required to be assigned to the connection C_i on the n-th carrier is calculated as follow:

$$a_n^i = \begin{cases} \left\lceil \frac{D_i \cdot T_{frame}}{[(L_n - H_n/S_n - T_n) \cdot S_n \cdot \eta_i]} \right\rceil, & w_n^i = 1 \\ 0 & w_n^i = 0 \end{cases} \tag{1}$$

Let b_n^i denotes the start timeslot allocated to the connection C_i on the n-th carrier, $1 \le b_n^i \le Y_n$. Since the timeslots used to support one connection must be contiguous in one carrier, the end timeslot allocated to the connection $e_n^i = b_n^i + a_n^i$. As a result, the start time p_i and the end time q_i of the duration for the connection C_i transmitting information are obtained as follows:

$$p_i = \left(b_n^i - 1\right) L_n \tag{2}$$

$$q_i = \left(e_n^i - 1\right) L_n \tag{3}$$

As mentioned above, there is no restriction 3 in the system we study here. Thus according to the system restrictions, we formulate the problem of the resource management in the MF-TDMA satellite communication system as follows:

$$\max_{w_n^i, m_i, b_n^i} \sum_{n=1}^{N} \sum_{i=1}^{W} w_n^i \tag{4}$$

s.t.

$$\sum_{n=1}^{N} \sum_{i=1}^{W} a_n^i \le Y_n \tag{5}$$

$$\sum_{n=1}^{N} w_n^i \le 1,\ \forall i \in \{1, \ldots, W\}, w_n^i = 0\, or\, 1 \tag{6}$$

$$p_j \ge q_k\, or\, q_j \le p_k,\ \forall j, k \in \mathcal{N}_i,\ j \ne k \tag{7}$$

The function (4) represents that the objective of optimization problem is maximization of the number of connections which are accessed to the system simultaneously. The conditions (5), (6) and (7) imply the restriction 1, restriction 4, and restriction 5, respectively.

It is noted that the optimization problem is nonlinear integer programming with constrains, which is NP-hard. NP-hard problems mean that the problem cannot be solved in in polynomial time. Thus we require a prohibitive amount of computation to obtain an optimal solution requires [8]. However, in the practical MF-TDMA satellite communication system, the NCC must deal with all the connection requests in the time of a frame. Therefore, it is impossible for the NCC to find optimal solution of the problem. To this end, in this paper we propose an approach to obtain a considerable solution. The approach is divided into two phases. In the former phase, we calculate the number of timeslots, which are required to be provided to each connection request. For the optimization problem, it is meant that we search a considerable value for w_n^i and m_i. In the latter phase, we allocate the timeslots in the frame structure. It is meant that we assign a value to b_n^i.

3 Phase I: Timeslot Calculation

It is seen from (1) that the number of the timeslots assigned to each connection request is determined by the carrier symbol rate and coding and modulation mode assigned to it. Here we decomposed the problem of timeslot calculation into two sub-problems: carrier assignment and coding and modulation mode assignment. Both of the two sub-problems are solved in finite time according to the proposed algorithm.

3.1 Sub-problem One: Carrier Assignment

In the time of a frame, the NCC will receive many connection requests from different terminals. The traffic demands of the connection requests are various. To this end, we propose an algorithm to assign each connection request to the different carriers according to its traffic demand. Let $\mathcal{F}$ denotes the set of the carrier, $\mathcal{F} = \{F_1, F_2,\ldots, F_N\}$. S_{total} denotes the sum of the carrier symbol rates. $\mathcal{C}$ denotes the set of traffic demand of the request connection, $\mathcal{C} = \{\mathrm{C}_1, \mathrm{C}_2,\ldots, \mathrm{C}_\mathrm{W}\}$. $\mathrm{D}_\mathrm{total}$ denotes the sum of the traffic demand of the connection requests. Without loss of generality, it is assumed that the elements in the $\mathcal{F}$ and $\mathcal{C}$ are sorted in ascending order in term of the symbol rate and the traffic demand, respectively. The algorithm is described as the following steps:

Step 1: Began with the first carrier in $\mathcal{F}$ and the first connection request in $\mathcal{C}$, T connection requests are assigned to the first carrier, the sum of traffic demand of the T connection requests is $\sum_{i=1}^{T} D_i \leq D_{total}S_1 \Big/ S_{total} \leq \sum_{i=1}^{T+1} D_i$.

Step 2: Update the set of $\mathcal{F}$ and $\mathcal{C}$, $\mathcal{F} \leftarrow \mathcal{F}$-$\{F_1\}$, $\mathcal{C} \leftarrow \mathcal{C}$-$\{C_1, C_2, \ldots, C_T\}$. If all the connection requests have been assigned to the carriers, then terminate the algorithm. Otherwise, jump to step 1.

According to the above algorithm, the connection request with high traffic demand will be assigned on the high symbol rate carrier, thus the period for the connection transmitting data, which is calculated according to (1)-(3), will be smaller. Therefore, the adverse effect of the restriction 5 on other connection requests from the same terminal will be reduced.

3.2 Sub-problem Two: Coding and Modulation Assignment

Now the modern terminal supports multiple coding and modulation modes. According to 0, a flexible coding and modulation mode assignment to the connection C_i must satisfy the link budget equation given as follows:

$$[M^i] = [\left(\frac{C}{T}\right)^i] - [\left(\frac{C}{T}\right)_{th}^i] \geq \text{CONSTANT} \tag{8}$$

$$\left(\frac{C}{T}\right)_{th}^i = \left(\frac{E_b}{n_0}\right)_{th}^i \cdot D_i \cdot k \tag{9}$$

where.

$[x] = 10\log(x)$,

M^i: link margin of the connection, which must be larger than a certain constant to guarantee the quality of the connection,

k: Boltzmann constant,

$(C/T)^i$: carrier-to-noise ratio of the total link, which is calculated as the following equations:

$$\left\{(C/T)^i\right\}^{-1} = \left\{(C/T)^i_{up}\right\}^{-1} + \left\{(C/T)^i_{down}\right\}^{-1} \tag{10}$$

$$\left(\frac{C}{T}\right)^i_{up} = \frac{EIRP^i_{ET}}{L^i_U} \cdot \left(\frac{G}{T}\right)_S \tag{11}$$

$$\left(\frac{C}{T}\right)^i_{down} = \frac{EIRP^i_S}{L^i_D} \cdot \left(\frac{G}{T}\right)^i_{ER} = \frac{EIRP^i_{ET} G_S}{L^i_U L^i_D} \cdot \left(\frac{G}{T}\right)^i_{ER} \tag{12}$$

where.

$(C/T)^i_{up}$: carrier-to-noise ratio of the uplink,

$(C/T)^i_{down}$: carrier-to-noise ratio of the downlink,

$EIRP^i_{ET}$: transmitting *EIRP* of the source terminal,

L^i_U: loss of the uplink, which consists of the rain loss, free space loss and other losses,

$(G/T)_S$: G/T value of the satellite receive system,

$EIRP^i_S$: the transmitting *EIRP* of the satellite,

G_S: gain of the satellite,

L^i_D: loss of the downlink,

$(G/T)^i_{ER}$: G/T value of the destination terminal.

Generally speaking, the bandwidth efficiency of the coding and modulation mode is higher, the power efficiency is lower. When the connection request adopts a higher order coding and modulation mode, the number of the timeslot assigned to the request is smaller, it is easy for the NCC to allocate the timeslots to the request. However, the transmitting power of terminal is higher. On the contrary, when the connection request adopts a lower order coding and modulation mode, the requirement of the transmitting power is lower. However, it is difficult for the NCC to assign enough timeslots for the request. To this end, we propose an algorithm to dynamically assign the coding and modulation mode to each connection request, taking into account a compromise between the system capacity and terminal transmitting power. The flowchart of the algorithm is described in Fig. 4.

The proposed algorithm dynamically assigns coding and modulation mode to the connection requests which have been assigned on the same carrier. At the beginning of the proposed algorithm, each connection request is assigned to the lowest order coding and modulation mode in order to save the transmitting power of the terminal. If the sum of timeslot assigned to the all the connection request is bigger than the total timeslots of the carrier, then the connection request with the biggest link margin is chosen to adopt the one order higher coding and modulation mode, which is most possible to support the higher coding and modulation mode. Therefore, the algorithm obtains a compromise between the transmitting power of each terminal and system capacity.

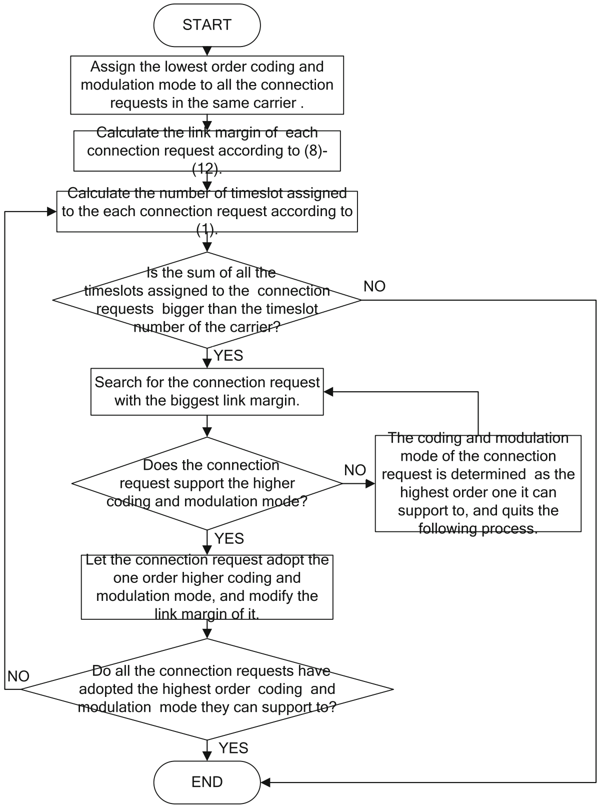

Fig. 4. Flowchart of the algorithm for coding and modulation mode assignment.

When the carrier and coding and modulation mode assigned to each connection are determined, the number of timeslots assigned to it is calculated according to (1). Then the next phase of resource management is allocating the assigned timeslots in the frame structure.

4 Phase II: Timeslot Allocation

In this section, we aim to solve the problem that how to allocate the calculated timeslots in the frame structure. The problem can be viewed as a variant of the bin-packing problem, which is NP-hard 2. As mentioned above, there is no restriction 3 in the system studied here. Thus the timeslot allocation problem is simpler than that of 2 and 3, and the advantage of the proposed RCP-Fit and RCP-A algorithm in above papers isn't obvious. To this end, we propose a heuristic algorithm called BF-modified algorithm, whose computational complexity is much lower than the algorithms mentioned in the above two papers. The process of the proposed algorithm is described as follows (Fig. 5).

In the algorithm, the carrier, which has the longest free time (free time means that the time hasn't been allocated to any connection request), is prepared to allocate timeslots

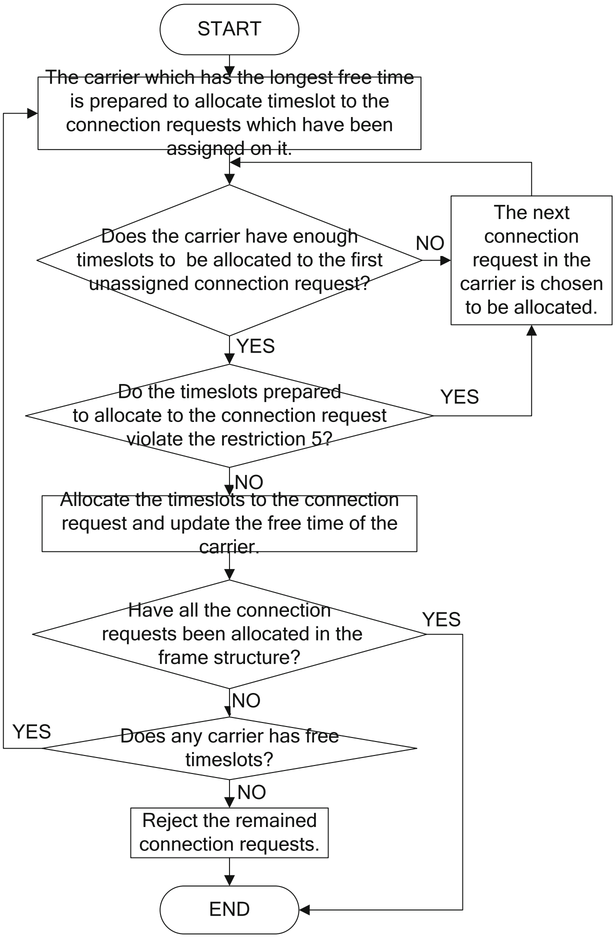

Fig. 5. Flowchart of the algorithm for timeslot allocation.

to the connection request. If there are no free timeslot or all the connection requests have been allocated in the frame structure, then the algorithm is terminated.

5 Simulation Results and Analysis

5.1 Simulation Parameter and Performance Measure

For the simulation, a MF-TDMA satellite communication system model is set up, the parameters of the system is given in Table 1.

The source and destination of each connection is randomly distributed among the twenty terminals. The traffic demand of the connection request is an exponential distribution with the mean value w.

To show the efficiency of the proposed approach, two measures are defined as follows:

Table 1. Parameters of the MF-TDMA system.

Frame length (ms)	110
Carrier number	4
Carrier symbol rate	64K, 2 × 64K, 4 × 64K,8 × 64K
Timeslot length in each carrier (ms)	10, 7, 5.5, 3
Timeslot header (symbol)	128
Timeslot tail (ms)	0.1
Terminal kind	6
Terminal number	20
Coding and modulation mode	BPSK (1/2),QPSK (1/2), QPSK (3/4),8PSK (3/4), 8PSK (7/8),16PSK (7/8)
Bit error rate	$e{-}6$
$\left(E_b/n_0\right)_{th}$(dB)	3,4.2,5.4,6.5,7.8,9.8
EIRP of each kind terminal (dBW)	76,68,64,60,48,43
G/T of each terminal (dB)	31,25,22,19,12.5,12

Traffic rejection ratio (**TRR**):

$$\sum_j D_j \Big/ \sum_{i=1}^{W} D_i, j \in \mathcal{R}$$

where $\mathcal{R}$ is the set of the rejected connection requests.

Timeslot utilization rate (**TUR**):

$$\sum_j A_j \Big/ \sum_{i=1}^{Z} A_i, j \in \mathcal{U}$$

where A_j is the number of symbol in the j-th timeslot, Z is total number of the timeslot, $\mathcal{U}$ is set of the used timeslots.

5.2 Efficiency of the Dynamical Adjustment of the Coding and Modulation Mode

In the phase of timeslot calculation, the coding and modulation mode of each connection is dynamically adjusted, depending on the total traffic demand generated by all the connection requests. The adjustment is clearly shown in the Fig. 6, where mode 1 and mode 6 represent the coding and modulation mode of BPSK(1/2) and 16PSK(7/8), respectively. It is seen that for the same number of the connection request, when the mean value of the traffic demand is larger, the occupation rate of mode 6 is higher. It means that when the traffic demand is higher, the bandwidth efficiency of coding and modulation

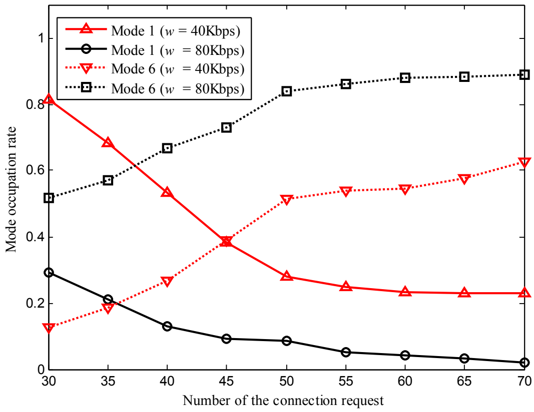

Fig. 6. Mode 1 and mode 6 occupation rate in term of the number the connection requests.

mode adopted by each connection request is higher. According to (1), the number of the timeslot assigned to each connection request is smaller, therefore, more connection requests are admitted to be accessed to the system. For the same reason, when the mean value of the traffic demand is same, the number of the connection requests is more, the bandwidth efficiency of coding and modulation mode adopted by each connection request is higher.

To show the advantage of the proposed dynamic adjustment of the coding and modulation mode, we compare it with the following two approaches:

1. Maximum Mode: All the connection requests adopt the maximum coding and modulation modes, which are calculated according to the link budget equation.
2. Minimum Mode: All the connection requests adopt the minimum coding and modulation.

For the simulations, the mean value of the traffic demand of each connection request is set to be 60 Kbps.

Figures 7, 8 and 9 show the comparison of the EIRP, timeslot utility rate and traffic rejection rate for the three approaches of the coding and modulation mode assignment, respectively. It is seen that when the traffic demands generated by all the connection requests are low, the approach of the maximum mode doesn't utilize the timeslot efficiently, causing a waste of the bandwidth and an unnecessary increase of the power. For example, when the number of the connection request is 30, the timeslot utility rate is only 47.13% and the total EIRP of the approach increases by 20.44%, compared with the approach of dynamic adjustment mode. On the contrary, the timeslot utility rate of the approach of the minimum mode is almost 100%, regardless of the total traffic demand. However, since the number of the timeslots which should to be assign to each connection request is high, the traffic rejection rate of the approach of minimum mode is the highest one among the three approaches. To overcome the drawbacks of the two approaches of the maximum and minimum mode, the approach of dynamic adjustment mode obtains a compromise between total transmitting power and the system capacity.

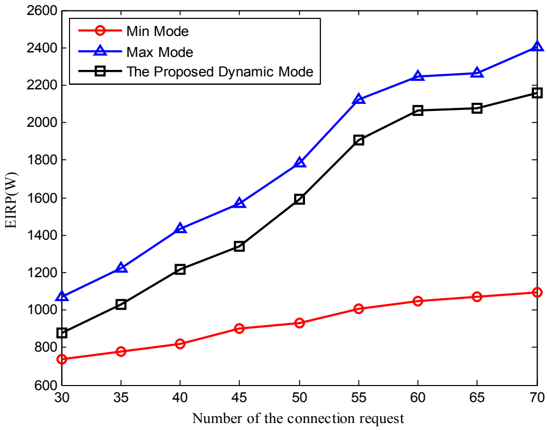

Fig. 7. Comparison of total EIRP of all the connection requests for the three approaches of the coding and modulation mode assignment.

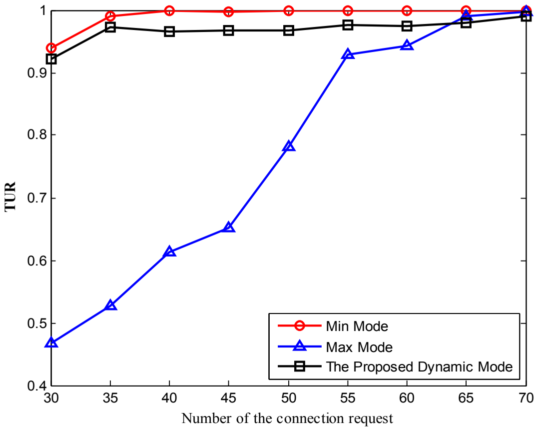

Fig. 8. Comparison of timeslot utility rate for the three approaches of the coding and modulation mode assignment.

It is noted that the total transmitting power of the approach is lower than that of the approach of maximum mode at the cost of traffic rejection rate slightly increases, and the traffic rejection rate of the approach is lower than that of the approach of minimum mode by the way of increasing the transmitting power.

5.3 Efficiency of the Proposed Timeslot Allocation Algorithm

To show the efficiency of the proposed BF-modified algorithm, we compare the proposed algorithm with the CSF algorithm proposed in 7. The CSF algorithm allocates the connection requests one carrier by on carrier. When all the connection requests on

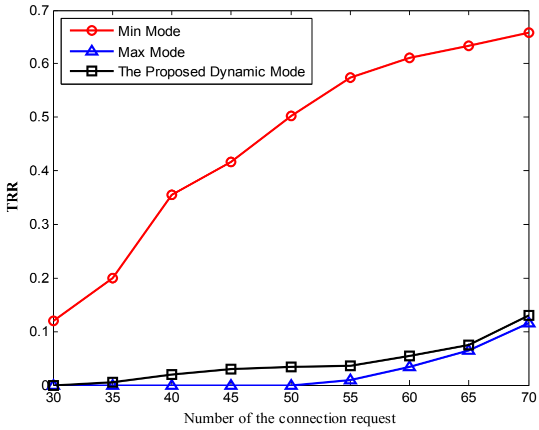

Fig. 9. Comparison of traffic rejection rate for the three approaches of the coding and modulation mode assignment.

one carrier have been allocated, the connection requests on the next carrier begin to be allocated.

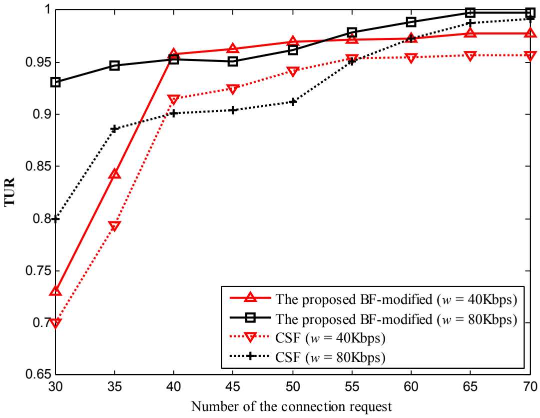

Fig. 10. Comparison of timeslot utility rate for the two timeslots allocation algorithms.

Figure 10 shows the timeslot utility rate (TUR) in term of the number of the connection request. It is seen that although total traffic demands generated by all the connection requests are various, the timeslot is sufficiently used due to the dynamical adjustment of the coding and modulation mode. In addition, the proposed BF-modified algorithm reduces the collision caused by the restriction 5, thus the TUR of the proposed algorithm is higher than that of the CF algorithm.

Figure 11 shows the traffic refused rate (TRR) in term of the number of the connection request. It is shown that the TRR of the proposed BF-modified algorithm is less than that of the CSF algorithm. For example, when the number of the connection requests is 55 and

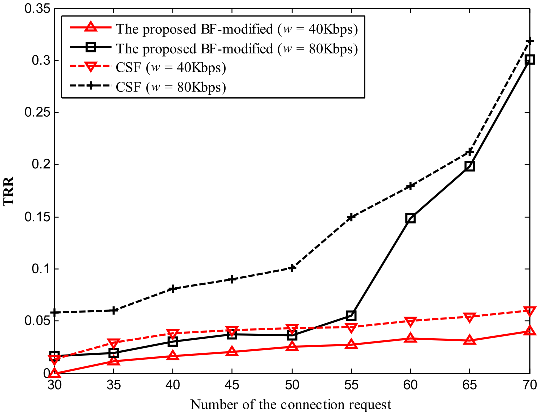

Fig. 11. Comparison of traffic refused rate for the two timeslots allocation algorithms.

the mean value of the traffic demand is 80 Kbps, the proposed BF-modified algorithm reduces the TRR by ten percent. Therefore, the proposed BF-modified algorithm supports more connection requests simultaneity, and it is more efficient than the CSF algorithm.

6 Conclusion

In this paper, we formulated the problem of the resource management in the MF-TDMA satellite communication system, and employed a practical approach to solve the NP-hard problem. The approach was divided into two phases: timeslot calculation and timeslot allocation. In the former phase, we proposed an algorithm to dynamically adjust the coding and modulation of each connection request according to the channel condition and state of the system resource usage. When the total traffic demand is high, a higher order modulation and coding mode is chosen for each connection request to admit more connection request. When the total traffic demand is low, a lower order modulation and coding mode is chosen for each connection request to save the transmitting power of each terminal. In the latter phase, we allocated the timeslots assigned to each connection request in the MF-TDMA frame structure, and we proposed an algorithm called BF-modified, which outperformed the existing CSF algorithm.

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