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PAPER

A Highly Efficient DAMA Algorithm for Making Maximum Use of both Satellite Transponder Bandwidth and Transmission Power

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SUMMARY This paper proposes a novel satellite channel allocation algorithm for a demand assigned multiple access (DAMA) controller. In satellite communication systems, the channels' total bandwidth and total power are limited by the satellite's transponder bandwidth and transmission power (satellite resources). Our algorithm is based on multi-carrier transmission and adaptive modulation methods. It optimizes channel elements such as the number of sub-carriers, modulation level, and forward error correction (FEC) coding rate. As a result, the satellite's transponder bandwidth and transmission power can be simultaneously used to the maximum and the overall system capacity, i.e., total transmission bit rate, will increase. Simulation results show that our algorithm increases the overall system capacity by 1.3 times compared with the conventional fixed modulation algorithm.

key words: *satellite communication, channel allocation, adaptive modulation, multi-carrier transmission, DAMA*

1. Introduction

In the past several years, multi-media traffic on satellite communication (SATCOM) systems has been rapidly increasing. During this time, SATCOM R&D activity has mainly focused on enhancing system capacity (the system's total transmission bit rate). Since every signal must go through a single satellite, the amount of usable radio resources is limited to the amount of satellite resources available, i.e. , satellite's transponder bandwidth (hereafter satellite bandwidth) and satellite transmission power (hereafter satellite power). Thus, the system capacity is inseparably connected to the satellite' s resources and their utilization. It is expected that the ongoing development of high power satellites, multi-beam systems, and Ka-band systems will expand satellite resources [1], [2]. However, implementing these technologies entails extremely high initial costs, because they require new communication satellites to be launched. A promising solution to this problem would be to develop a channel allocation algorithm to enhance the system capacity without the need for a new satellite launch.

Hopes are high that multi-carrier decomposition [3] and the adaptive modulation and coding (AMC) will enable satellite resources to be used more effectively. However, these techniques do not address the problem of how best to use satellite bandwidth and satellite power together. To this end, we propose a novel satellite channel allocation algorithm for a demand assigned multiple access (DAMA) controller. The algorithm is based on a combination of multi-carrier decomposition and AMC. On the basis of previous work [4], [5], this paper details the calculation process for channel allocation and describes simulations that tested our algorithm's performance.

The rest of this paper is organized as follows. Section 2 describes the SATCOM system assumed here and clarifies the key channel allocation requirements. Section 3 describes the conventional channel allocation algorithm and points out its problems. In Sect. 4, we propose a channel allocation algorithm and show some examples of its use. In Sect. 5, we demonstrate the algorithm's effectiveness through computer simulations that apply it to various traffic situations.

2. System Concept

2.1 Construction

Our target system is depicted in Fig. 1. The system mainly consists of a base station, a DAMA controller, several hundred earth stations, and a communication satellite. The communication satellite amplifies the signals from an earth station and the base station and sends them down to the service area. These signals are transmitted on a traffic channel or a control channel.

Signals for channel request and channel release are transmitted using a control channel. They are transmitted by time-division multiplexing (TDM) on the forward link (from base station to earth station) and slotted ALOHA on the return link (from earth station to base station). On the other hand, data signals are transmitted on traffic channels, each of which is occupied by the signals of one earth station multiplexed by frequency-division multiple access (FDMA). This paper focuses on the traffic channel allocation for each earth station's channel request.

2.2 Channel Allocation Procedure

An earth station communicates with other earth stations through a traffic channel. If the traffic channel is statically assigned to each earth station, satellite resources are wasted. This is because satellite resources are always needed even while the earth station does not communicate. Thus, the

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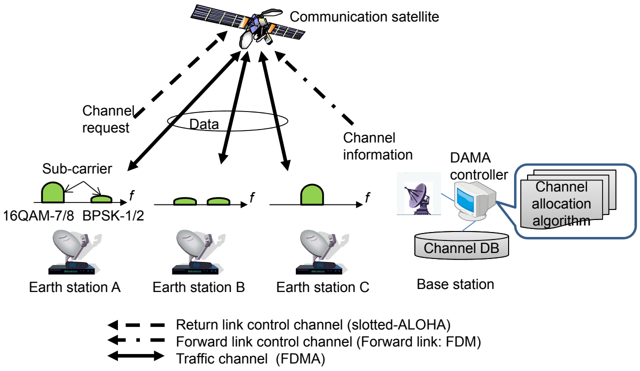


Fig. 1 Proposed SATCOM system

system uses the DAMA scheme [6] for making traffic channel assignments. The DAMA controller uses a channel allocation algorithm to determine traffic channel elements such as bandwidth, power, modulation level, and forward error correction (FEC) coding rate in accordance with a channel access sequence as follows:

(a) As shown in Fig. 2, a sending earth station uses the control channel to send a channel request signal including information on the required transmission bit rate to the base station. Typically this signal is transmitted by slotted ALOHA.

(b) The channel allocation algorithm determines a traffic channel element that satisfies the required transmission bit rate.

(c) The base station uses the control channel to assign the traffic channel to the sending and receiving earth station. At the same time, it registers the assigned channel information in the channel database (DB).

(d) The sending earth station communicates with the other receiving earth station by using the assigned traffic channel.

(e) After the communication ends, both earth stations send the release signal to the base station. When the base station receives it, the DAMA controller deletes the assigned traffic channel information from the channel DB.

2.3 Multi-carrier and AMC Functionalities

Since each earth station requests or releases a traffic channel on an individual basis, unused bandwidth in the satellite transponder is inevitably distributed. This being the case, a single-carrier transmission can only be used in a continuous bandwidth and frequency utilization is degraded. This is because channel allocation may fail even if the sum of the unused bandwidth is wide enough to accommodate the required bandwidth of the traffic channel. Our earth stations have a multi-carrier functionality [3] that can divide a single carrier into multiple sub-carriers, and thus they can use such discontinuous bandwidth.

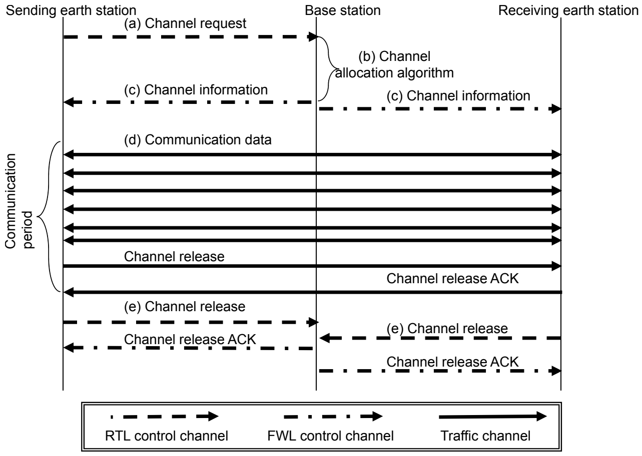
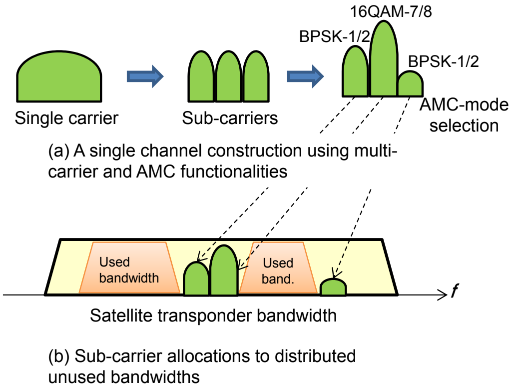


Fig. 2 Channel allocation procedure between earth stations



(a) A single channel construction using multi-carrier and AMC functionalities

(b) Sub-carrier allocations to distributed unused bandwidths

Fig. 3 Single channel allocation using multi-carrier and AMC functionalities

Moreover, to effectively utilize satellite resources, our earth stations also provide an AMC functionality since it can make use of the trade-off relationship between bandwidth and power by changing the AMC-mode (a combination of modulation level and FEC coding rate).

Figure 3 shows a single channel allocation using the multi-carrier and AMC functionalities. First, as shown in Fig. 3(a), multiple sub-carriers, each of which is identical in bandwidth but may be different in AMC-mode, are constructed. Next, as shown in Fig. 3(b), each sub-carrier is assigned to the unused bandwidth that other earth stations do not use.

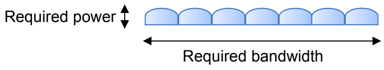
2.4 Channel Allocation Requirements

For simplicity, we will refer to a traffic channel as simply a “channel” hereafter. Thus, three channel elements for the system must be determined:

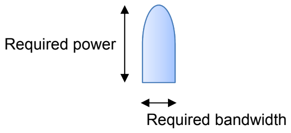
(1) the number of sub-carriers,

(2) the sub-carriers’ AMC-mode, and

(3) the sub-carriers’ frequency.

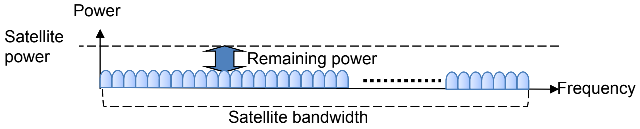


(a) Fixing low required E_b/N_0 AMC-mode (ex. BPSK-1/2)

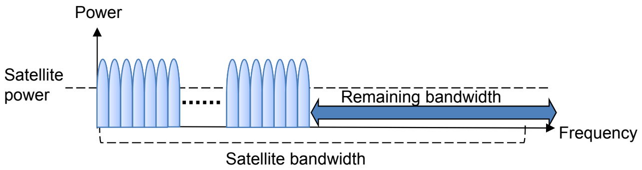


(b) Fixing high required E_b/N_0 AMC-mode (ex. 16QAM-7/8)

Fig. 4 Single channel resources when fixing AMC-modes



(a) Fixing low required E_b/N_0 AMC-mode (ex. BPSK-1/2)



(b) Fixing high required E_b/N_0 AMC-mode (ex. 16QAM-7/8)

Fig. 5 Multiple channel allocations using the conventional algorithm

However, the channel allocation algorithms described in this paper mainly focus on channel elements (1) and (2) to enhance resource utilization. The reason is that this decision is not relevant to the resource utilization since the channel element (3) is determined in accordance with the unused bandwidth of the satellite transponder. Each AMC-mode (see Table 4 for example) has an energy per bit to noise power density ratio (E_b/N_0) and spectrum efficiency η given by the product of the modulation level and FEC error coding rate. Therefore, channel allocation requirements are as follows:

(i) The total transmission bit rate of all sub-carriers that belong to one channel exceeds the required transmission bit rate of a user.

(ii) The received E_b/N_0 of each sub-carrier surpasses the required E_b/N_0 that is prescribed for the selected AMC-mode.

3. Conventional Algorithm and its Problems

Designing an applicable channel allocation algorithm is extremely important for enlarging the overall SATCOM system capacity. The simplest way to allocate channels is to fix the AMC-mode such that it is identical for all earth stations and the transmission power is adjusted to meet the required E_b/N_0. This idea is what we refer to as the "**conventional algorithm**" in this paper.

In the conventional algorithm, the required bandwidth W_{req} is uniquely decided by using the required transmission bit rate R_{req}:

$$W_{req} = \lceil \frac{R_{req}}{\eta(x)W_0}(1+\sigma)\rceil W_0 \quad , \tag{1}$$

where x is an identifier of the fixed AMC-mode, $\eta(x)$ is the spectrum efficiency of the fixed AMC-mode, W_0 is the sub-carrier bandwidth ($W_0 = 100kHz$ in this paper), σ is a roll-off factor for avoiding signal distortion ($\sigma = 0.25$ in this study), and $\lceil o \rceil$ is an operator to provide the smallest integer that is greater than o. As shown in Eq. (1), W_{req} is inevitably quantized in multiples of the sub-carrier bandwidth. The power supplied by the communication satellite is

$$P_{sat\_req} = E_b/N_0(x)\eta(x)N_0W_{req}\frac{L_d}{G_{earthr}G_{sats}}, \tag{2}$$

where $E_b/N_0(x)$ is the required E_b/N_0 of the fixed AMC-mode, N_0 is the noise power density (W/Hz) in the received signal, L_d is the free space loss on the satellite downlink, G_{earthr} is the receiving earth station's antenna gain and G_{sats} is satellite antenna gain of the sending side.

Assuming σ, N_0, L_d, and G_{earthr} are constant for all earth stations, Eqs. (1) and (2) respectively show that the satellite resources' usage only depends on the fixed AMC-mode's identifier x and the required transmission bit rate R_{req}. Accordingly, a single channel' s resources to satisfy the constant required bit rate can be illustrated as in Fig. 4. If we choose a low E_b/N_0 AMC-mode (e.g. BPSK-1/2), the required bandwidth (=number of sub-carriers) tends to be wide while the required power from communication satellite tends to be low. On the contrary, if we choose a high E_b/N_0 AMC-mode (e.g. 16QAM-7/8), the required bandwidth tends to be narrow while the required power from communication satellite tends to be high.

Figure 5 shows a multiple channel allocation in which the channels are allocated until their total allocated bandwidth or total allocated power reaches the satellite bandwidth or satellite power. In a low E_b/N_0 AMC-mode, when the total allocated bandwidth reaches the satellite bandwidth upper limit, no more channels can be allocated even if the total allocated power does not reach the satellite power upper limit (Fig. 5(a)). Conversely, in a high E_b/N_0 AMC-mode, when the total allocated power reaches the satellite power upper limit, no more channels can be allocated even if the total allocated bandwidth reaches the satellite bandwidth upper limit, (Fig. 5(b)). It thus depends on which AMC-mode is chosen as to whether satellite bandwidth or satellite power runs out first.

In the previous two cases, left-over satellite resources remain because the conventional algorithm determines the channel elements independently of the residual bandwidth and power of the satellite. Consequently, the main problem with the conventional algorithm is that it does not allow the satellite bandwidth or the satellite power to be fully utilized.

We refer to this problem as the "**residual resources problem**" in this paper.

4. Proposed Algorithm

The main purpose of our channel allocation algorithm is to avoid the residual resources problem. To do this, our algorithm first seeks a number of "**channel candidates**", each of which is a combination of sub-carriers of different AMC-modes, to satisfy the required transmission bit rate. Then it chooses the candidate that provides the best utilization of satellite resources.

4.1 Related Researches

Orthogonal frequency-division multiplexing (OFDM) is widely used for ground based wireless or wire systems such as ADSL, VDSL, PLC (power line communication), WLAN, LTE, and WiMAX. Although OFDM offers multi-carrier and AMC functionalities like our algorithm, its purpose differs. OFDM controls the AMC-mode of each sub-carrier to compensate for degradation of signal quality due to changes in the user' s propagation environment. If a particular range of frequencies suffers from interference or attenuation, the carriers within that range can be disabled or made to run slower by applying a more robust AMC-mode to those sub-carriers.

However, OFDM does not address the problem of how to effectively use both bandwidth and power in channel allocation under the severe restrictions of the total bandwidth and total power that can be used by the whole system. That is, OFDM-based systems assume that power is supplied from a ground power line, and hence, they have few restrictions on total power usage. On the other hand, SATCOM systems have a severe restriction on total power usage because the power is only supplied by the solar panels of the communication satellite.

The water filling technique maximizes system capacity in wireless systems [7, 8]. This technique likens the noise spectrum to the geographical bottom of a lake and the transmitted power of each user to water that accumulates (like the total transmitted power) in the lake to a certain level that deliverd the maximum capacity of the channel. However, the optimal power obtained in this way does not account for SATCOM systems' constraints in the channel allocation, such as on-demand channel allocations/releases, maximum transmitted power of each user, selectable ACM-modes, or quantized frequency usage.

4.2 Channel Allocation Outline

The channel allocation of our algorithm is shown in Fig. 6. For simplicity, the figure only shows channel allocation, because the channel release is not relevant to the resource utilization. The allocation is carried out as follows:

(Step I) Information about the required transmission bit rate is taken from the channel request signal.

(Step II) Channel candidates that satisfy the required transmission bit rate are identified. For example, Fig. 6-II shows three candidates having 5 sub-carriers, 3 sub-carriers, and 2 sub-carriers, respectively. Each sub-carrier may have different AMC-mode identifiers, i.e., 1, 2, 3 and 4 that correspond to BPSK (modulation level) - 1/2 (FEC error coding rate), QPSK-1/2, QPSK-7/8, and 16QAM-7/8. Note that our channel allocation algorithm can use other AMC-modes besides those listed above [**?**, 5].

(Step III) The best channel among the channel candidates is the one that minimizes the evaluation value γ (See Sect. 4.6). For example, Fig. 6-III shows three sub-carriers whose AMC-mode identifiers are 3, 2, and 2. Since a smaller evaluation value means less of a residual resource problem and less required radio resources (bandwidth and power), this step enhances resource utilization efficiency.

(Step IV) Each sub-carrier is assigned to the unused bandwidth in the satellite transponder. Since this step is not relevant to the resource utilization, we shall not describe it in any more detail.

(Step V) Steps I to IV are performed whenever a new channel allocation request occurs. We should note that previously allocated channels are not reallocated when a new channel is allocated in step V. This is because the algorithm uses Eqs. 8 and 9, which include the current channels' total bandwidth and power.

In following steps I to V, our algorithm can maximally utilize the satellite bandwidth and satellite power simultaneously when the number of allocated channels increases. Thus, it increases the system capacity. The following sections describe our algorithm in detail. Although the description covers one-way traffic channels (from sending station to receiving station), it is also good for two-way traffic whose channels are individually allocated.

4.3 Channel Candidate Calculation

The algorithm first seeks a number of "**channel candidates**", each of which is a combination of sub-carriers of different AMC-modes to satisfy the required transmission bit rate. Defining $D(j)$ as the number of sub-carriers of the j_{th} channel candidate, $\eta(i, j)$, the spectrum efficiency of the i_{th} sub-carrier and j_{th} channel candidates, and χ a limitation factor on the maximum transmission bit rate, the channel candidates will satisfy

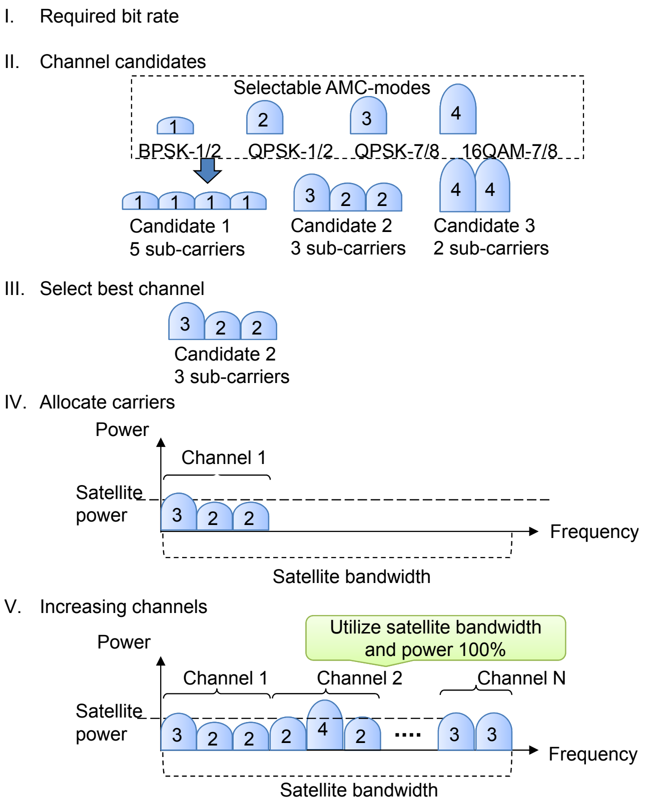


Fig. 6 Channel allocation procedure using the proposed algorithm

$$R_{req} \leq \sum_{i=1}^{D(j)} \eta(i, j) W_0 \leq \chi R_{req} \text{ note } \chi \geq 1. \tag{3}$$

Although a larger χ tends to give more candidates, it permits excessive bit rates and wastes power and bandwidth. Our prior examinations used $\chi = 1.3$, and this choice resulted in a dozen channel candidates or so for the required transmission bit rate (hundreds of kbps). For example, Tables 1 and 2 show the channel candidates when $R_{req} = 600kbps$ and $R_{req} = 450kbps$. In the former case, the candidate identifier $j = 1$ has fourteen sub-carriers with BPSK (modulation)-1/2 (FEC coding rate), and each candidate exceeds the required transmission bit rate, even though its subcarriers have different AMC-modes.

Since the conventional algorithm simply calculates the channel elements using Eqs. (1) and (2), the calculation finishes in an instant. However, our algorithm needs some time to find the channel candidates, and this time increases with the number of candidates. Thus, our algorithm may have a disadvantage in the form of a channel access delay. To reduce this delay, we used a mathematical optimization technique called dynamic programming [9].

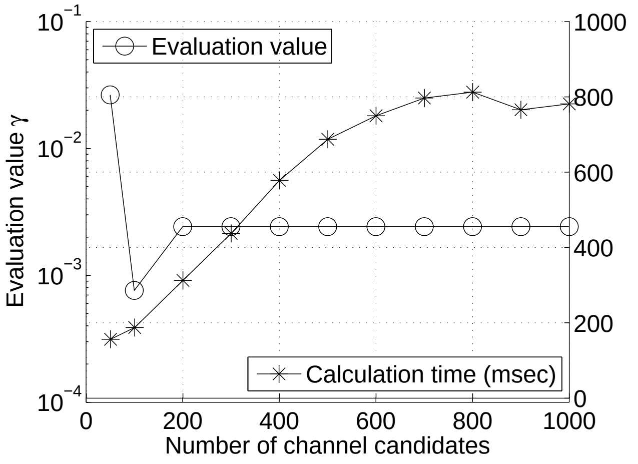


Fig. 7 Convergence of evaluation value and required calculation time

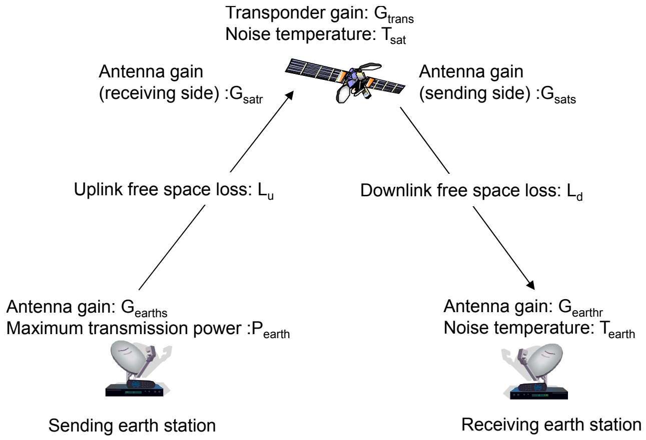


Fig. 8 Reference model for channel design

To estimate a sufficient number of channel candidates, we analyzed the relation between the obtained minimum evaluation value γ (See Sect. 4.6) and the number of channel candidates, as shown in Fig. 7. The plot also shows the calculation time needed to find the candidates when $R_{req} = 1600kbps$. As can be seen, the evaluation value converged when there were more than 200 candidates. The calculation time for 200 candidates was approximately 300 ms using an Intel core i7-920 2.67 GHz processor. The time is negligible in comparison with the interval between channel requests (several minutes), and hence, there is no drawback in using our algorithm as far as the channel access delay goes.

4.4 Required Power and Bandwidth

Figure 8 shows a reference model from the sending earth station to the receiving earth station. The model is used in calculating the channel’ s power and bandwidth. Ignoring the interference from other radio systems, the noise power density N_0 (W/Hz) in the received signal can be written as

$$N_0 = \frac{G_{sats} G_{trans} G_{earthr}}{L_d} \left(T_{sat} + \frac{L_d}{G_{sats} G_{trans} G_{earthr}} T_{earth}\right) \kappa, \tag{4}$$

where G_{sats} is the satellite antenna gain of the sending side,

Table 1 Example of channel determination when the required transmission bit rate is 600 kbps

Candidate identifier j	Number of AMC-modes allocated				Trans. bit rate (kbps)	Bandwidth util. $W_r(j)$	Power util. $P_r(j)$	St. Power util. $E_r(j)$	$\alpha(j)$	$\beta(j)$	$\gamma(j)$
	BPSK-1/2	QPSK-1/2	QPSK-7/8	16QAM-7/8							
1	19	0	0	0	760	0.2714	0.0453	0.1086	0.16	0.28	0.044
2	18	0	0	0	720	0.2571	0.0429	0.1029	0.15	0.26	0.039
3	17	0	0	0	680	0.2429	0.0405	0.0971	0.14	0.25	0.035
4	16	0	0	0	640	0.2286	0.0381	0.0914	0.13	0.23	0.031
5	15	0	0	0	600	0.2143	0.0357	0.0857	0.13	0.22	0.027
6	13	1	0	0	600	0.2000	0.0360	0.0862	0.12	0.2	0.024
7	11	2	0	0	600	0.1857	0.0362	0.0867	0.11	0.19	0.02
8	9	3	0	0	600	0.1714	0.0364	0.0872	0.095	0.18	0.017
9	7	4	0	0	600	0.1571	0.0366	0.0877	0.085	0.16	0.014
10	5	5	0	0	600	0.1429	0.0368	0.0882	0.075	0.15	0.011
11	3	6	0	0	600	0.1286	0.0370	0.0887	0.065	0.13	0.0087
12	1	7	0	0	600	0.1143	0.0372	0.0892	0.055	0.12	0.0066
13	0	6	1	0	620	0.1000	0.0421	0.1009	0.041	0.11	0.0044
14	0	4	2	0	600	0.0857	0.0443	0.1063	0.029	0.096	0.0028
15	1	0	4	0	600	0.0714	0.0513	0.1229	0.014	0.088	0.0012
16	1	0	2	1	600	0.0571	0.0837	0.2006	0.019	0.1	0.0019
17	1	0	0	2	600	0.0429	0.1161	0.2783	0.052	0.12	0.0064

Selected number j=15, $W_{agn} = 0.50MHz, P_{agn} = 0.03W$

Table 2 Example of channel determination when the required transmission bit rate is 450 kbps

Candidate identifier j	Number of AMC-modes allocated				Trans. bit rate (kbps)	Bandwidth util. $W_r(j)$	Power util. $P_r(j)$	St. Power util. $E_r(j)$	$\alpha(j)$	$\beta(j)$	$\gamma(j)$
	BPSK-1/2	QPSK-1/2	QPSK-7/8	16QAM-7/8							
1	14	0	0	0	560	0.2857	0.1197	0.0800	0.12	0.31	0.036
2	13	0	0	0	520	0.2714	0.1174	0.0743	0.11	0.3	0.032
3	12	0	0	0	480	0.2571	0.1150	0.0686	0.1	0.28	0.028
4	10	1	0	0	480	0.2429	0.1152	0.0691	0.09	0.27	0.024
5	8	2	0	0	480	0.2286	0.1154	0.0696	0.08	0.26	0.02
6	6	3	0	0	480	0.2143	0.1156	0.0701	0.07	0.24	0.017
7	4	4	0	0	480	0.2000	0.1158	0.0706	0.06	0.23	0.014
8	2	5	0	0	480	0.1857	0.1160	0.0711	0.049	0.22	0.011
9	0	6	0	0	480	0.1714	0.1162	0.0716	0.039	0.21	0.0081
10	0	4	1	0	460	0.1571	0.1185	0.0770	0.027	0.2	0.0054
11	1	0	3	0	460	0.1429	0.1254	0.0936	0.012	0.19	0.0024
12	1	0	1	1	460	0.1286	0.1578	0.1713	0.021	0.2	0.0042
13	0	0	0	2	560	0.1143	0.2001	0.2726	0.061	0.23	0.014

Selected number j=11, $W_{agn} = 1.00MHz, P_{agn} = 0.06W$

T_{sat} is the satellite noise temperature, G_{trans} is the satellite transponder gain, G_{earthr} is the antenna gain of the receiving earth station, T_{earth} is the earth station' s noise temperature, L_d is the free space loss on the satellite downlink, and κ is the Boltzmann constant.

Since the received E_b/N_0 of each sub-carrier has to correspond to the required E_b/N_0, the transmission power for the j_{th} channel candidate is

$$P_{req}(j) = \sum_{i=1}^{D(j)} E_b/N_0(i,j)\eta(i,j)N_0W_0\times \frac{L_dL_u}{G_{earthr}G_{sats}G_{trans}G_{satr}G_{earths}}, \quad (5)$$

where $E_b/N_0(i,j)$ is the required E_b/N_0 of the i_{th} sub-carrier and j_{th} channel candidates, L_u is the free space loss on the satellite uplink, and G_{earths} is the sending earth station's antenna gain. In addition, the required bandwidth of the j_{th} channel candidate is

$$W_{req}(j) = D(j)W_0. \quad (6)$$

4.5 Utilization Ratio of Available Resources

$P_{sat\_req}(j)$ given by Eq. 7 is the transmission power of the satellite transponder when that of the earth station is $P_{req}(j)$.

$$P_{sat\_req}(j) = P_{req}(j)\frac{G_{earths}G_{satr}G_{trans}}{L_u}$$

$$= \sum_{i=1}^{D(j)} E_b/N_0(i,j)\eta(i,j)N_0 W_0 \frac{L_d}{G_{earthr} G_{sats}}. \tag{7}$$

Using Eq. (4)-Eq. (7), we define the satellite bandwidth utilization ratio $W_r(j)$, satellite power utilization ratio $W_r(j)$, and earth station power utilization ratio $E_r(j)$ as

$$W_r(j) = \frac{W_{req}(j) + W_{agn}}{W_{sys}}, \tag{8}$$

$$P_r(j) = \frac{P_{sat\_req}(j) + P_{agn}}{P_{sys}}, \textit{ and} \tag{9}$$

$$E_r(j) = \frac{P_{req}(j)}{P_{max}} \tag{10}$$

where W_{sys} is the satellite bandwidth, W_{agn} is the total bandwidth for the previously assigned channels, P_{sys} is the satellite's maximum transmission power, P_{agn} is total satellite power for the previously assigned channels, and P_{max} is the earth station's maximum transmission power.

$W_r(j)$ shows how much of the satellite bandwidth is occupied after the new channel is allocated using the j_{th} channel candidate (the same applies to $P_r(j)$). Moreover, $E_r(j)$ shows how much power is required vis-a-vis the maximum transmission power. To allocate the new channel within the available satellite bandwidth, satellite power, and earth station transmission power, the following equations must hold simultaneously:

$$W_r(j) \leq 1, \tag{11}$$

$$P_r(j) \leq 1, \textit{ and} \tag{12}$$

$$E_r(j) \leq 1. \tag{13}$$

4.6 Channel Determination using Optimization Norm

Figure 9 shows the relationship between $W_r(j)$ and $P_r(j)$ of the channel candidates identifier j. In the figure, the lengths of $\alpha(j)$ and $\beta(j)$ are respectively calculated as

$$\alpha(j) = |W_r(j) - P_r(j)| \tag{14}$$

$$\beta(j) = \sqrt{W_r(j)^2 + P_r(j)^2} \tag{15}$$

The shorter $\alpha(j)$ is, the better the balance of the satellite bandwidth and satellite power usage tends to be. The shorter $\beta(j)$ is, the less the satellite bandwidth and satellite power usage becomes. Since we can consider that a shorter $\alpha(j)$ and $\beta(j)$ results in more efficient utilization of satellite resources, our channel allocation algorithm reduces the following evaluation value $\gamma(j)$ (the product of $\alpha(j)$ and $\beta(j)$) by adjusting $W_{req}(j)$ and $P_{req}(j)$.

$$\gamma(j) = \frac{|W_r(j) - P_r(j)|}{\sqrt{2}} \times \sqrt{W_r(j)^2 + P_r(j)^2}. \tag{16}$$

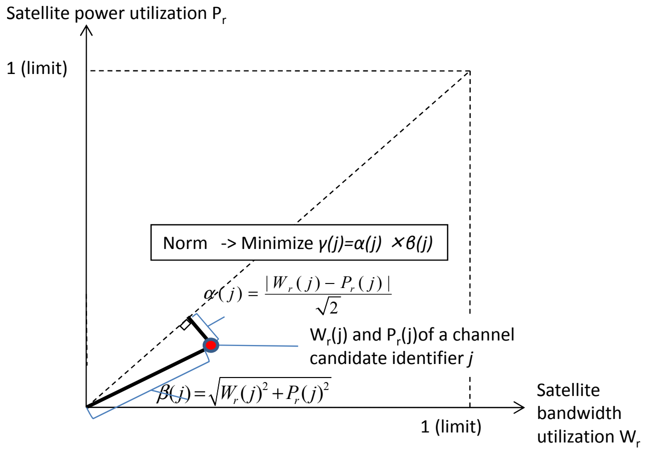


Fig. 9 Satellite resource utilization and algorithm norm

If $W_r(j)$ and $P_r(j)$ concurrently become larger than those of the other channel candidates, the channel allocation may waste bandwidth and power. To avoid this problem, we carry out the "**channel selection process**. First, candidates having the same number of sub-carriers are made into a group. Then, the channel candidates with the minimum $P_r(j)$ are chosen from each group. Finally, one candidate that has the minimum evaluation value $\gamma(j)$ is chosen from the selected ones.

Figure 10 shows the example of the channel selection process. Since channel candidates A, B, and C have identical $W_r(j)$, i.e. the same number of sub-carriers, they make a group. If channel candidate B or C were selected, the channel would waste power; that is, channel candidate A has the minimum $P_r(j)$ of the three. According to the resource utilization efficiency requirement, we must not choose the channel candidate only on the basis of their evaluation values. Therefore, channel candidate A is chosen from this group.

For simplicity, we will refer to the selected channel candidates as simply "channel candidates" hereafter. Our algorithm determines the best channel that minimizes $\gamma(j)$ among the channel candidates while satisfying Eq. (11)-(13). As a result, $W_r(j)$ and $P_r(j)$ are always very close and the residual resource problem hardly ever occurs. Since Eqs. 8 and 9 take the total bandwidth and total power for previously assigned channels into consideration, our algorithm enhances resource utilization without having to reallocate previously assigned channels.

4.7 Channel Allocation Results

Let us illustrate an example of channel allocation using our algorithm. The parameters are listed in Table 3. The first channel request is issued under the following conditions: $W_{agn} = 0MHz, P_{agn} = 0W$[†], and $R_{req} = 600kbps$. The calculation results of $W_r(j), P_r(j), E_r(j)$, and $\gamma(j)$ are shown

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[†] This means the system does not have previously allocated channels.

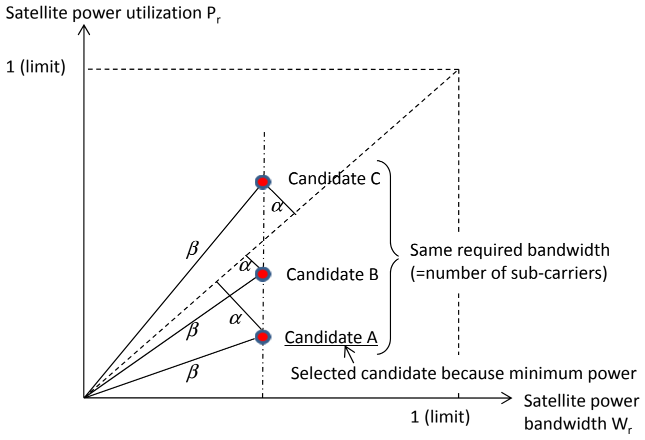


Fig. 10 Channel selection process among channel candidates

in Table 1.

The best candidate identifier that gives the minimum $\gamma(j)$ and satisfies Eqs. (11)-(13) is $j = 15$. Thus, our algorithm allocates 1 and 4 sub-carriers whose AMC-modes are respectively BPSK-1/2 and 16QAM-7/8. After the first allocation, the assigned resources change to $W_{agn} = 0.5MHz$ and $P_{agn} = 0.03W$. A second channel request $R_{req} = 450kbps$ is issued, and the results for it are shown in Table 2. Since the best candidate is at $j = 11$, the algorithm allocates 1 and 3 sub-carriers whose AMC-modes are respectively BPSK-1/2 and 16QAM-7/8.

These channel allocation examples show that the channel components will vary depending on how the previously assigned channels and the required transmission bit rate are accounted for. We can also see that after each channel allocation is performed, the used satellite bandwidth and power are mostly at significantly low levels. For example, Fig. 11 plots the relationship between the satellite bandwidth utilization and satellite power utilization for channel candidates for the first allocation. The figure also shows the original channel candidates before the channel selection process described in Sect. 4.6. The final 13 candidates are chosen from the original 200, and the best candidate (circled in the figure) is determined from among these 13. The $\alpha(j)$ and $\beta(j)$ lengths of the best candidate are significantly shorter than those of the other candidates. This means our algorithm improved the resource utilization in this case.

5. Overall Performance

5.1 Simulation Set up

We performed computer simulations to demonstrate the features of our algorithm and compare it with the conventional algorithm described in Sect. 3. At the outset of the simulations, the earth station required a one-way traffic channel and the required transmission bit rate was varied from 200 kbps to 900 kbps in 100 kbps steps (see Fig. 12(a)) We used four AMC-modes, as shown in Table 4. The other system parameters are listed in Table 3. The simulations were carried out until either the total bandwidth or total power of the allocated channels reached their upper limit.

Table 3 System parameters

Item		Symbol	Value
Sub-carrier bandwidth		W_0	100 (kHz)
Satellite	Bandwidth	W_{sys}	7 (MHz)* 14 (MHz)**
	Power	P_{sys}	0.5 (W)* 2.0 (W)**
	Antenna gain	G_{sats} G_{satr}	42.0 (dB) 42.0 (dB)
	Transponder gain	G_{trans}	110 (dB)
	Noise temperature	T_{sat}	316.3 (K)
	Roll off factor	σ	0.25
Free space loss	Downlink	L_d	205.5 (dB)
	Uplink	L_u	206.8 (dB)
Earth station	Maximum transmission power	P_{earth}	8 (W)
	Antenna gain	G_{earths} G_{earthr}	41.0 (dB) 41.0 (dB)
	Noise temperature	T_{earth}	316.3 (K)

(*) Section 4.7, (**) Section 5

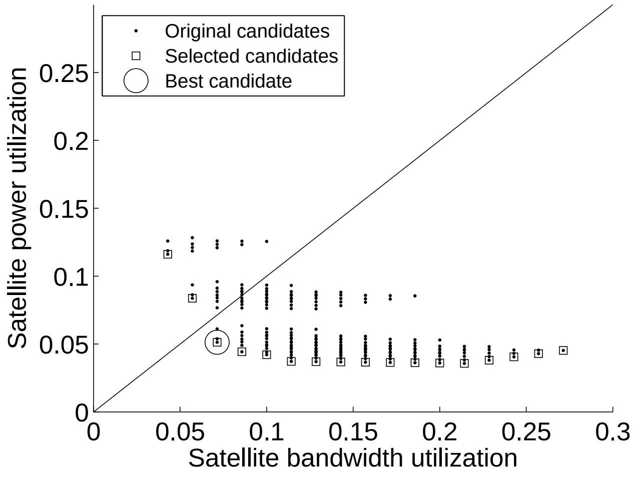


Fig. 11 Example of channel candidates and best selection

5.2 Channel Elements

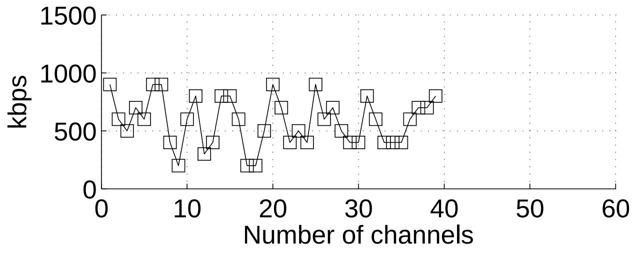
Figure 13 shows the variation in the number of sub-carriers together with the AMC-mode used. Both algorithms adjusted the number of sub-carriers so that the channels' transmission bit satisfied the required transmission bit rate. Moreover, our algorithm adjusted the AMC-mode so that it could be different for each sub-carrier, whereas the conventional algorithm fixed it so that it would be the same for all sub-carriers.

5.3 System Capacity

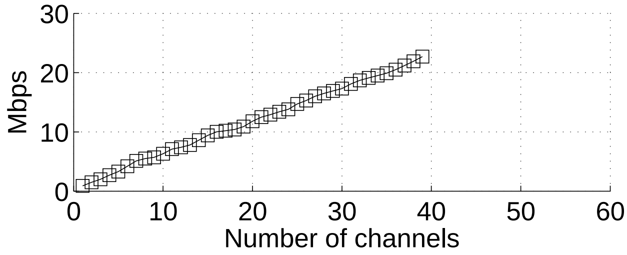
System capacity was defined as the cumulative required transmission bit rate at the end of simulation (see Fig. 12(b)). Figure 14 shows variations in the satellite bandwidth utilization and satellite power utilization for each allocated

Table 4 Variation in AMC-modes

Identifier	Notation	Modulation (level)	Coding rate	Efficiency (bps/Hz)	Required E_b/N_0(dB)
1	BPSK-1/2	BPSK (1)	1/2	0.5	4.6
2	QPSK-1/2	QPSK (2)	1/2	1.0	4.8
3	QPSK-7/8	QPSK (2)	7/8	1.75	6.3
4	16QAM-7/8	16QAM (4)	7/8	3.5	10.0



(a) Required bit rate



(b) Cumulative bit rate

Fig. 12 Channel request patterns

channel. As discussed in Sect. 3, satellite resources are frequently left over with the conventional algorithm, and the amount of remaining resources depends on the AMC-mode, which is fixed. As a result, system capacity decreases. One promising way to solve this problem is to choose an "**optimal AMC-mode**" that provides the largest system capacity from among the available AMC-modes shown in Table 4.

Table 5 summarizes the system capacity results shown in Fig. 14. The optimal AMC-mode is QPSK-7/8; it maximally provides 17.7 Mbps that accommodates 31 channels. Even if the AMC-mode is optimal, 55% of the satellite power remains unused, as shown in Fig. 14(b). In contrast, our algorithm provides 22.7 Mbps, which accommodates 39 channels and completely avoids the residual resources problem, as shown in Fig. 14(d). The increase from 17.7 to 22.7 Mbps means that with our algorithm the system capacity is about 1.3 times greater than it is with the conventional algorithm.

5.4 Resource Efficiency

To ascertain the reason for the capacity enhancement, we define the availability rate as

Table 5 Algorithm' s Performance

Algorithm	System capacity	
	(Mbps)	(Ch.)
Conventional QPSK-1/2	10.6	19
Conventional QPSK-7/8 (optimal AMC-mode)	17.7	31
Conventional 16QAM-7/8	14.6	26
Proposed	22.7	39

(*) optimal AMC-mode

$$S_r(l) = \frac{R_t(l)}{R_{req}(l)}, \tag{17}$$

where l is the allocated channel number, $R_t(l)$ is the transmission bit rate, and $R_{req}(l)$ is the required transmission bit rate for the l_{th} channel. This equation shows that fewer resources are used in the channel allocation as S_r approaches 1. Figure 15 shows the cumulative probability distribution obtained by the algorithms. This figure shows that our algorithm gives a smaller S_r than the conventional algorithm, and we can conclude from it that our algorithm allocates resources more efficiently than the conventional algorithm does, given the same required transmission bit rate.

6. Conclusion

This paper introduced a highly efficient satellite channel allocation algorithm for a demand assigned multiple accesses (DAMA) controller. Our algorithm makes maximum use of the satellite's transponder bandwidth and transmission power simultaneously in situations where each earth station requires a different transmission bit rate. Our algorithm is based on a novel resource control technique that combines multi-carrier transmission and adaptive modulation. Simulation results show that the total transmission bit rate provided by our algorithm is at least 1.3 times what the conventional algorithm can provide.

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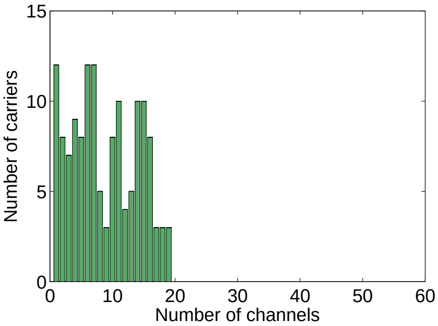
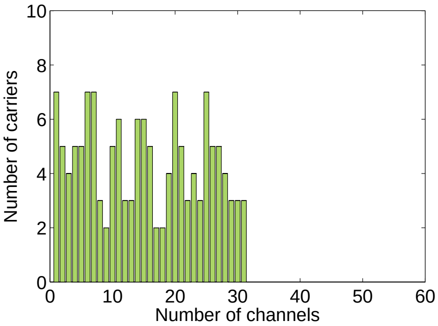
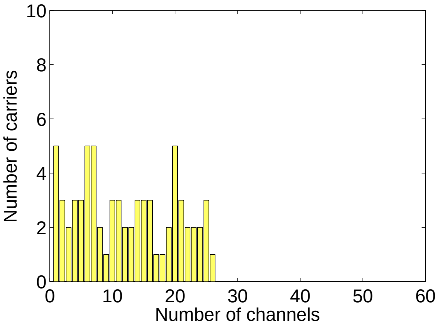


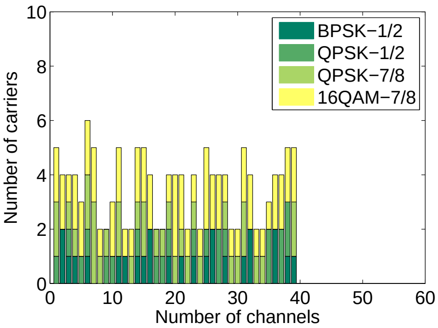
(a) Conventional with QPSK−1/2



(b) Conventional with QPSK−7/8

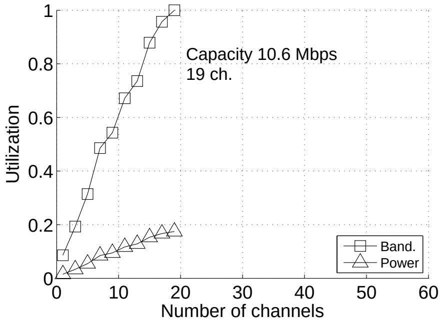


(c) Conventional with 16QAM−7/8

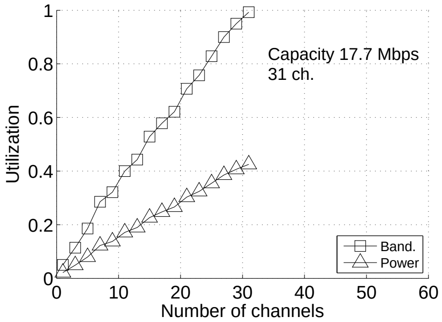


(d) Proposed algorithm

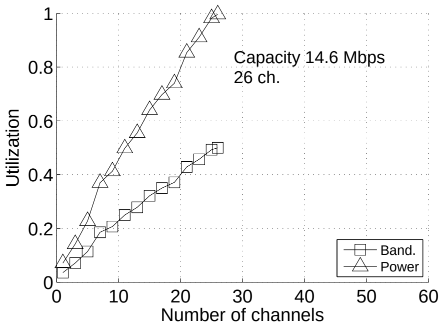
Fig. 13 Allocated sub-carrier constructions



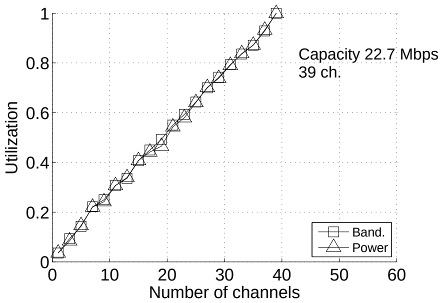
(a) Conventional with QPSK−1/2



(b) Conventional with QPSK−7/8

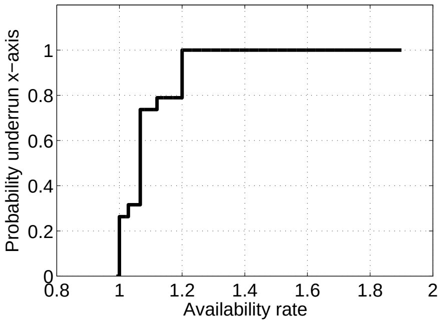


(c) Conventional with 16QAM−7/8

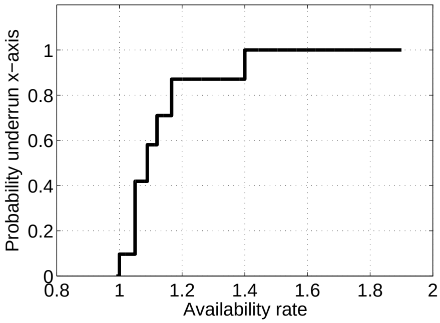


(d) Proposed algorithm

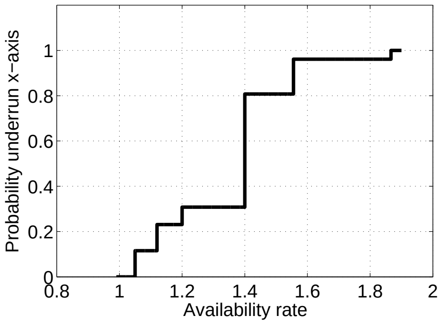
Fig. 14 Satellite resource utilization



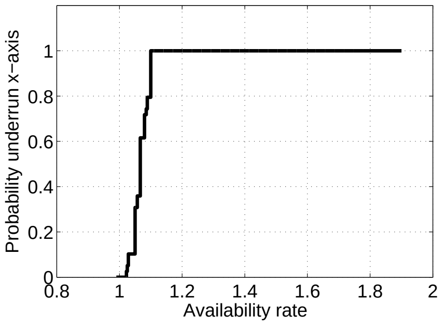
(a) Conventional with QPSK−1/2



(b) Conventional with QPSK−7/8



(c) Conventional with 16QAM−7/8



(d) Proposed algorithm

Fig. 15 Analysis of resource utilization efficiency

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