Flexible Capacity Allocation in Smart Gateway Diversity Satellite Systems Using Matching Theory

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Abstract. In this paper, we investigate the performance of multi-beam high throughput satellite systems that employ the smart gateway diversity concept. The multi-beam satellite system is examined under the satellite system's capacity losses, the impact of the channels' atmospheric effects, the offered capacities of gateways and finally the requested capacities of users' beams. To ameliorate the system's performance, a novel flexible resource allocation algorithm is proposed which is based on the matching theory concept. Gateways and users' beams are matched according to the aforementioned factors applying the deferred acceptance algorithm. Simulation results illustrate that the proposed matching scheme outperforms a less sophisticated fixed, i.e. without resource management, allocation scheme in terms of system's capacity losses, rendering the former a very promising allocation mechanism for future satellite systems.

Keywords: Smart gateway diversity · Resource allocation
Multi-beam satellite · Matching theory · Deferred acceptance algorithm

1 Introduction

The wireless users' demands for broadband internet services are growing extremely due to the enormous technological progress in devices such as smartphones, tablets and laptops. Cisco predicts that 78% of the world's mobile data traffic will be video by 2021 [1]. The terrestrial LTE-Advanced (4G) cellular systems are not able to follow the tremendous demand in video services. Afterwards, to fulfill the prospects of the aforementioned synchronous challenges in wireless communication networks a turn into the exploitation of satellite networks has been made. Especially, satellite systems are ideal for rural and suburban areas where the terrestrial networks have limited connectivity due to the less number of subscribers.

The satisfaction of users' high bit rate requirements gives rise to multi-beam satellite systems in which each gateway (GW) serves a number of user beams and makes feasible the exploitation of gateway diversity techniques. The application of

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satellite communication networks for broadband internet satellite services has been included in the second generation of Digital Video Broadcasting for Satellite Transmission DVB-S2 standard and in its extension DVB-S2X [2]. The exploitation of Ka Band (20–30 GHz) for satellite transmission and the multi-beam earth coverage are efficient ways to support the users' high throughput demands that need extra bandwidth resources at a significant lower cost for satellite operators.

The huge traffic demands lead to very high data rates for future satellite communication systems which target to values of hundreds Gigabits/s up to Terabit/s [3, 4]. Hence, higher frequency bands, such as Q/V Band (40–50 GHz), are also investigated. Especially, in these systems the use of Q/V Band at the feeder link (the link between the gateway and the satellite) and the Ka Band at the user link (the link between the satellite and the user (UE) beam) are examined. However, in case that the operating frequency is above 10 GHz, the performance of the system is deteriorated by the atmospheric effects [5]. Rain attenuation is the dominant fading mechanism and can exhibit several dBs for a small but crucial for the availability of the systems time percentage.

To deal with the severe signal degradations in Ka and Q/V Bands and for a more efficient use of ground and space resources, smart gateway diversity paradigms are proposed [4, 6, 7] and developed for the mitigation of attenuation taking into account the spatial and temporal behavior of the atmospheric effects and radio channel conditions. In the smart gateway techniques the service of a user beam by a specific gateway can change and be routed to another gateway, if the former's link is unable to serve the user beam's requirements. More specifically, there are two types of smart gateway diversity schemes. The first scheme is called N + P scheme where there are N active GWs and P redundant. A GW of the P redundant is set on operation in case that one of the first N gateways in on outage due to the atmospheric attenuation.

The second scheme is called N-active scheme, all gateways are active, but in case that one of the gateways goes in outage, the traffic is served forwards to the other active GWs while the bit rate decreases since smaller bandwidth is used. The N-active scheme is separated into frequency multiplexing in which each UE beam is served simultaneously by different GWs in different frequency carriers and time multiplexing in which each UE beam is served by different GWs in different time slots. The latter architecture is similar to the implemented Satellite Switched TDMA (SS-TDMA).

In [6] the N-active time multiplexing scheme is investigated under a flexible resource allocation management in a multi-beam SS-TDMA system with four GWs and four UE beams. Particularly, the matching among the UE beams and GWs is examined based on the UEs' capacity requirements and the GWs' offered capacities. Three different allocation algorithms are proposed targeting to the maximization of throughput and to balance the traffic between the UE beams considering the feeder links' propagation conditions. The simulation results prove the outperformance of proposed algorithms in terms of system's losses compared with a fixed allocation scheme. In [7] besides the performance investigation of the aforementioned resource allocation algorithms, the availability performance in N + P and N-active schemes is also examined.

Recent literature, such as [6, 7], shows the importance of flexible resource allocation algorithms for having better performance towards to the direction of High Throughput Satellite (HTS) communication networks. Considering the above aspect, this paper investigates the use of matching theory in satellite communication systems which is applied in such systems for first time according to authors' best knowledge. Matching theory [8, 9] is a mathematical tool which describes a distributed and self-optimizing approach to take resource management decisions efficiently. This theory, based on the two sided approach, contains two different sets of agents and creates mutually beneficial relations among them through the application of an efficient stable matching algorithm, known as deferred acceptance algorithm (DAA) [9]. In our case the satellite networks can be modeled as matching markets, where each agent of one set, i.e. GW/UE, ranks the agents of the other set, i.e. UEs/GWs (correspondingly), using a preference relation which is based on their utility functions. Moreover, it is noticeable that matching theory has a wide practical impact through its implementation in many real world systems, such as the U.S. National Resident Matching Program.

In this paper the flexible resource allocation, based on GWs' offered capacities and UE beams' requirements, in a multi-beam HTS SS-TDMA network is investigated using the matching theory. In Sect. 2, a brief description of time series synthesizer proposed in [10] is given and in Sect. 3, the basic concepts of matching theory are described to have a better understanding. In Sect. 4, the system model is described in detail while in Sect. 5, numerical results of the performance of our proposed matching algorithm are given. Finally in Sect. 6, conclusions derived from the present paper are described.

2 Multi-dimensional Rain Attenuation Synthesizer

In this Section we describe the generation of time series of rain attenuation which has been considered for modeling the links' propagation conditions and extracting the corresponding Carrier-to-Noise-and-Interference Ratio (CNIR).

In [11] a first-order stochastic differential equation (SDE) is proposed for the generation of time series of rain attenuation, called as the Maseng-Bakken model (M-B). The main assumptions of the model are that rain attenuation follows the log-normal distribution and that the rate of change of rain attenuation is proportional to the instantaneous value of rain attenuation. In [10], based on the SDE of [11], a multidimensional SDE is presented for simulating correlated in spatial domain rain attenuation time series at multiple sites which has the following form:

$$d\mathbf{a}_t = \mathbf{F}(\mathbf{a}_t)dt + \mathbf{Z}(\mathbf{a}_t)d\mathbf{W}_t \tag{1}$$

where $\mathbf{a}_t = \left[a_t^1, \ldots, a_t^n\right]^T$ is the vector of rain attenuation at the different sites. Rain attenuation on each link $a_t^i, i = 1, \ldots, n$ follows the lognormal distribution with standard deviation of its natural logarithm σ_{a_i} and median value a_{m_i}. The joint distribution is joint lognormal with covariance matrix $\mathbf{C}$. The other coefficients of (1) are:

$$\begin{aligned}
\mathbf{F}(\mathbf{a}_t) &= \left[F_1\left(a_t^1, \ldots, a_t^n\right), \ldots, F_n\left(a_t^1, \ldots, a_t^n\right)\right]^T \\
\mathbf{Z}(\mathbf{a}_t) &= \left[z_{ij}\left(a_t^1, \ldots, a_t^n\right)\right]_{1 \le i,j \le n} \\
\mathbf{W}_t &= \left[W_t^1, \ldots, W_t^n\right]^T
\end{aligned} \tag{2}$$

with $\mathbf{W}_\mathrm{t}$ the n-dimensional Brownian Motion, which means that $W_t^1, \ldots, W_t^n$ are independent Brownian Motions [12]. According to the model presented in [10], the coefficients $\mathbf{F}$ and $\mathbf{Z}$ must be chosen in such way that the diffusion coefficient of each stochastic process is proportional to the instantaneous value of rain attenuation on the specific link and second the transformation of (3) will yield to the form of (4).

$$X_t^i = \ln\left(\frac{a_t^i}{a_{m_i}}\right), i = 1, \ldots, n \tag{3}$$

$$d\mathbf{X}_t = \mathbf{B}\mathbf{X}_t dt + \mathbf{S} d\mathbf{W}_t \tag{4}$$

where $\mathbf{X}_t = \left[X_t^1, \ldots, X_t^n\right]^T$ is the vector of the random process X_t^i, with initial values $\mathbf{X}_0 = \mathbf{x}_0$ and $\mathbf{B}$ is a n × n matrix with elements $b_{ij} = -\beta_i \delta_{ij}$ where δ_{ij} is the Kronecker delta function and β_i is the dynamic parameter as this is defined on the M-B model. The analytical solution of (4) is [10, 12]:

$$\mathbf{X}_t = e^{t\mathbf{B}}\mathbf{X}_0 + e^{t\mathbf{B}} \int_0^t e^{-s\mathbf{B}} \mathbf{S} d\mathbf{W}_s \tag{5}$$

Assuming a correlation coefficient as the one presented in [13] the covariance matrix of the random process $\mathbf{X}_\mathrm{t}$ is:

$$\mathbf{C}_\mathbf{X} = \begin{bmatrix} \sigma_{a_1}^2 & \cdots & \rho_{n,1n}\sigma_{a_1}\sigma_{a_n} \\ \vdots & \ddots & \vdots \\ \rho_{n,n1}\sigma_{a_n}\sigma_{a_1} & \cdots & \sigma_{a_n}^2 \end{bmatrix} \tag{6}$$

Therefore, for (4) denoting:

$$\mathbf{G} = \mathbf{S}\mathbf{S}^T \tag{7}$$

it holds from [10], (5) and the theory of multidimensional SDEs [10] that:

$$[G]_{ij} = \left(\beta_i + \beta_j\right)[C_X]_{ij} \tag{8}$$

So, in order to fulfill the requirements denoted at the beginning of this Section the coefficients $\mathbf{F}$ and $\mathbf{Z}$ must be:

$$F_i(\mathbf{x}) = x_i \left[-\beta_i \ln \frac{x_t^i}{a_{m_i}} + \frac{1}{2}\sum_{j=1}^{n} s_{ij}^2\right] \tag{9}$$

and

$$z_{ij}(\mathbf{x}) = x_i s_{ij} \tag{10}$$

The methodology for the calculations of the rain attenuation time series is fully described in [11].

3 Basic Concepts of Matching Theory

In this Section some basic concepts of matching theory are provided in order to be able to understand thoroughly the proposed matching scheme which leads to the mutually acceptable and efficient GW-UE beam pairing. In following notions we use the terms UE and UE beam interchangeably. The matching theory is applied to two different sets of agents, i.e. GWs and UE beams and is based on specific utility functions, defined below as U, according to their preferences. Due to the fact that in our scenario each GW can serve at most one UE beam and each UE beam can be served by at most one GW, the investigated matching is called as one-to-one matching approach.

The fundamental element of matching theory is the matching function μ, which is formally defined as follows for the investigated system scenario:

Definition 1 [8]: A matching μ is a function from the set $\mathbf{GWs} \cup \mathbf{UEs}$ into the set of unordered families of elements of $\mathbf{GWs} \cup \mathbf{UEs}$ such that:

1. $|\mu(UE)| = 1$ for every UE $\in$ **UEs** and $\mu(UE) = \text{UE}$ if $\mu(UE) \notin$ **GWs**.
2. $\mu(UE) = \text{GW}$ if and only if UE is in $\mu(\text{GW})$.

Definition 2: Let M be the number of GWs and N the number of UEs. For any UE_n, a preference relation $\succ_n$, which consists a complete, reflexive and transitive binary relation between GWs and UEs, is defined over the set of M GWs such that, for any two GWs $i, j \in M$, $i \neq j$ and two matchings $\mu, \mu' \in M\,x\,N$, $i = \mu(n), j = \mu'(n)$:

$$(i, \mu) \succ_n (j, \mu') \Leftrightarrow U_{UE_n,i}(\mu) > U_{UE_n,j}(\mu') \tag{11}$$

The preference relation for GWs $\succ_m$ is defined similarly.

Each GW (UE) constructs a preference list of the UEs (GWs) based on its utility function according to (12), (13). Especially, the GWs' and UEs' preference vectors include the corresponding ordered lists $prefGW_k = \{UE_{k(i)}\}_{i=1}^{N}$ and $prefUE_j = \{GW_{j(i)}\}_{i=1}^{M}$, that are constructed according to the following conditions respectively:

$$U_{GW,k}(UE_{k(1)}) > \ldots > U_{GW,k}(UE_{k(N)}) \tag{12}$$

$$U_{UE,j}(GW_{j(1)}) > \ldots > U_{UE,j}(GW_{j(M)}) \tag{13}$$

The solution of the matching game is based on the DAA algorithm, described briefly in Sect. 4, according to which in a two-sided, one-to-one matching game a stable matching always exists [9]. It should be noted that a matching can be regarded as stable only if it leaves no pair of players on opposite sides who were not matched to each other but would both prefer to be. Finally, the runtime complexity of this algorithm is $O(MN)$ [9].

4 System Model

In this paper, we consider a multi-beam HTS SS-TDMA system with M GWs and N UEs' beams as depicted in Fig. 1. In a specific time instance each UE beam can be served by one GW and each GW can serve only one UE beam. The system scenario is investigated per a SS-TDMA frame period of 1 s similar to [6, 7], considering that the links' propagation conditions change slowly during the duration of 1 s [14]. Furthermore, the links between the satellite and UEs' beams are considered ideal and identical to investigate exclusively the performance of feeder links [6, 7].

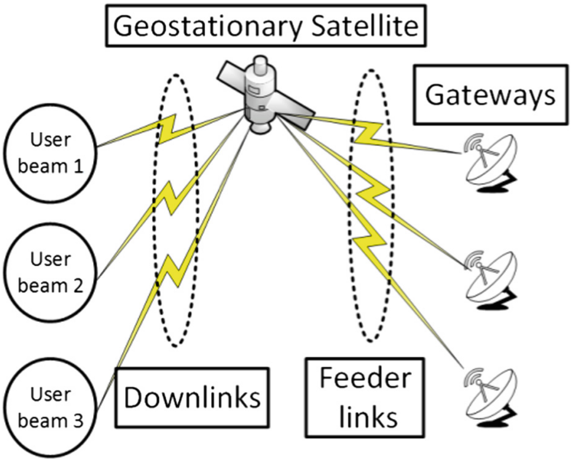

Fig. 1. System model

In each frame period each GW_i, $i = 1, \ldots, M$, offers capacity, defined as OC_i in bps, to UEs' beams. The offered capacity OC_i is expressed by the Shannon formula as follows:

$$OC_i = B_C \log_2(1 + \gamma_i) \tag{14}$$

where B_C is the carrier bandwidth and $\gamma_i^{-1} = CNIR_{up,i}^{-1} + CNIR_{dn}^{-1}$ is the total or end-to-end $CNIR_i$ including both the CNIR of feeder link i and the CNIR of downlink which is invariant in our scenario. Especially $CNIR_{up,i} = CNIR_{CS,i} 10^{-A_i/10}$, the $CNIR_{CS,i}$ is the CNIR in clear sky conditions for the feeder link i and A_i is the rain attenuation of the same link. Finally, we must consider that in above notions $CNIR = C/(N + I)$. In terms of UEs' beams, in each frame period the requested capacity of UE_j $j = 1, \ldots, N$ is defined as RC_j. Afterwards, the capacity losses are expressed as [6, 7]:

$$L = \sum_{j=1}^{N} \max\{RC_j - OC_j, 0\} \tag{15}$$

According to our proposed matching algorithm and based on (12), (13) and the expressions of offered and requested capacities, each GW sorts the UEs in a descend order, from larger to smaller values, based on latter's requested capacities. Hence, GWs are more willing to match with the UEs which request higher capacities. On the other hand, each UE sorts the GWs in a descend order based on latter's offered capacities. Consequently, UEs are more willing to match with GWs that offer higher capacities. This process results in the construction of preference vectors for each GW and UE beam.

We apply the DAA algorithm [9] which involves a number of "iterations". In first iteration each GW proposes to its most favorite UE, the first UE in the GW's preference list. Each UE matches with its most preferable GW, the first GW in the UE's preference list and rejects the proposals of the rest GWs. In each subsequent iteration, every rejected GW from the previous iteration proposes to the most preferred UE to whom it has not yet proposed. Each UE rejects proposals from unacceptable GWs and rejects also its current paired GW, if there is a proposal from a more preferable GW. The algorithm finishes when either all the GWs have been matched with UEs, or there are GWs that were rejected by all UEs acceptable to them.

Afterwards, we result in the GWs-UEs pairs and compute the system losses considering the requested capacity of each UE and the offered capacity to this UE, according to (15), after the matching process. Finally, our proposed pairing scheme is compared with a less sophisticated fixed allocation scenario where each feeder link is connected for equal number of frames to each downlink, without requiring any resource management.

5 Simulation Results and Discussion

For the numerical results we assume that there are four gateways in locations that can be found in [6, 7] and four UE beams. Every link between the gateway stations and the satellite operate at 50 GHz, the bandwidth $B_C = 1$ GHz, the uplink CNIR in clear sky conditions is 25 dB, assuming that it is the same for all the four gateways, while the corresponding CNIR for the downlink is 13 dB. Furthermore, the UEs' requested capacities are drawn from a uniform distribution in the range $(0, B_C \log_2(1 + CNIR_{\max}))$ bps where $CNIR_{\max}^{-1} = CNIR_{CS,up}^{-1} + CNIR_{CS,dn}^{-1}$. For the simulation of the rain attenuation time series, the statistical parameters of the lognormal distribution for each site are derived from the methodology described in [15] and the dynamic parameter of rain attenuation from [16, 17]. Finally, the system's performance in terms of capacity losses is investigated over a year.

Time series of rain attenuation for four GWs' locations similarly with the papers [6, 7] are evaluated and the outage probability of each GW may be computed by $P_{out} = P[CNIR \leq CNIR_{th}]$ indicating the time percentage that the CNIR of the GW is below a given threshold. Moreover, from the time series of GWs' CNIR, originated by the rain attenuation time series through the Shannon formula, the capacity time series for every link can be derived.

Figure 2 presents the gateways' transmitted capacities and the system's capacity losses based on (15). In the first subfigure the total offered capacity by gateways is depicted over time. In the second subfigure the capacity losses of proposed matching algorithm are illustrated, while the third subfigure shows the losses of the fixed allocation scheme. We remark that, generally, in deep fades the losses increase for both schemes, but the proposed matching mechanism results in fewer losses' events with lower values of capacity losses compared with the fixed mechanism.

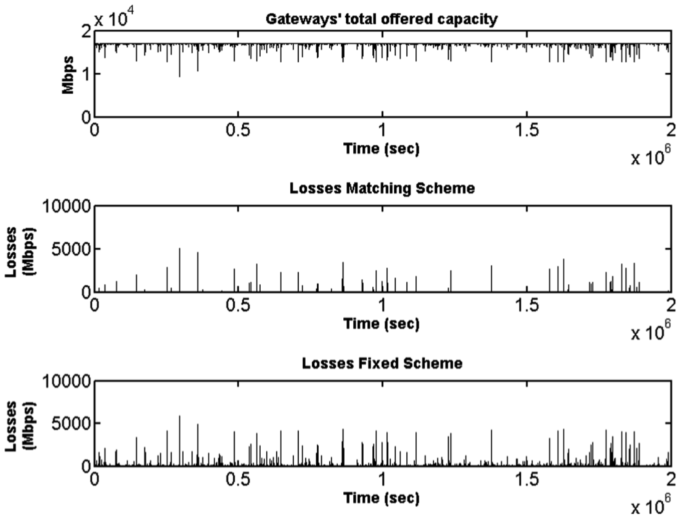

Fig. 2. A time series snapshot of gateways' offered capacities and system's capacity losses under matching and fixed allocation schemes.

Figure 3 presents the complementary cumulative distributions of the losses for both mechanisms as a percentage of instantaneous traffic demands. In Fig. 3(a) we examine the system without considering $CNIR_{th}$, assuming all the values of capacity losses over a year. The superiority of the proposed matching mechanism, resulting in much smaller probability losses than the fixed scheme, is obvious. In Fig. 3(b) we investigate the performance of both schemes for different probabilities $P = \{10\%, 1\%, 0.1\%\}$ resulting in $CNIR_{th} = \{12.63, 11.86, 3.72\}$ dB respectively evaluated from the corresponding capacity time series. The distributions contain the annual time instances for which $min\{CNIR_{GW_i}\} < CNIR_{th},\ i = 1, \ldots, 4$. The probability that the minimum of CNIR is less than a threshold gives the probability that at least one of the link has CNIR less than a defined threshold. It is remarkable that the matching scheme outperforms the fixed allocation for all different values of $CNIR_{th}$. Finally we obtain that as $CNIR_{th}$ decreases, resulting in more severe fading conditions, the probability of system's capacity losses increases for both mechanisms.

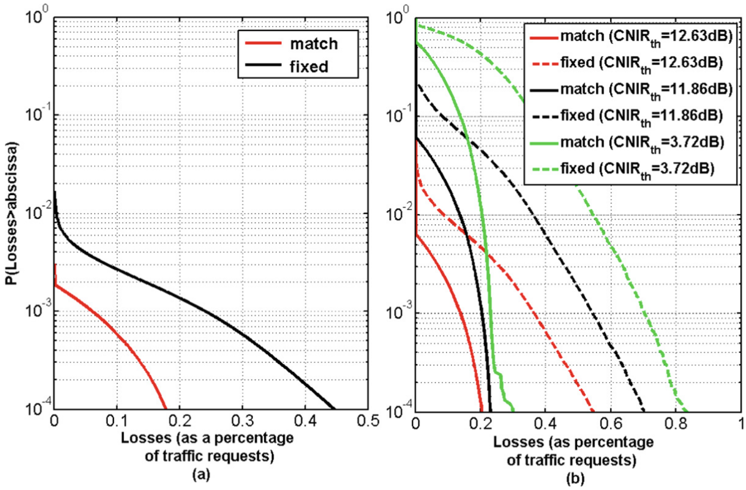

Fig. 3. Complementary cumulative distributions of the losses for both mechanisms, (a) without considering $CNIR_{th}$ and (b) with three different $CNIR_{th}$ values.

6 Conclusion

In this paper a novel flexible capacity allocation mechanism, based on the matching theory concept, in a multi-beam HTS SS-TDMA system has been proposed. The proposed mechanism relies on a smart gateway N-active time multiplexing scheme. For making appropriate and efficient matching among gateways and user beams the channels' propagation conditions, originated by a multi-dimensional rain attenuation synthesizer, the offered gateways' capacities and requested users' capacities are considered. The matching between the gateways and users' beams applies the deferred acceptance algorithm. Finally, the simulation results prove the superiority of the proposed scheme compared with a fixed allocation scheme in terms of system's capacity losses. The matching scheme results to fewer losses events with lower values of capacity losses compared with the fixed scheme.

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