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Energy-Aware Resource Management in Cloud Based Integrated Terrestrial-Satellite Networks

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Abstract

In this paper, we propose an architecture of cloud based integrated terrestrial-satellite networks, in which satellite and terrestrial networks that belong to the same operator cooperatively provide seamless coverage for mobile users. Meanwhile, a resource pool at the cloud acts as the integrated resource management and control center of the entire network. Then, based on the delay constraint of users, we formulate the resource allocation problem for the operator to minimize the energy consumption. By decomposing the optimization problem into two subproblems, we eventually obtain the optimal resource allocation strategies for the operator. Furthermore, numerical results are provided to evaluate the performance of the proposed strategies.

1 Introduction

To meet the increasing demand for communication, the 5G-Crosshaul architecture is aimming to achieve a software-defined reconfiguration of the entire network through a unified data plane and control plane [1]. As one possible application, cloud radio access network (C-RAN) has been proposed [2]. In C-RAN, the traditional base station (BS) is divided into the remote radio heads (RRHs), and the baseband unit (BBU) pool at the cloud, and most baseband processing procedures are then centralized at the BBU, which helps to improve both the spectrum efficiency and the energy efficiency. In [3], limited computation resources were considered and the minimum power consumption problem was discussed by jointly optimizing hybrid clustering and computation provisioning.

While terrestrial cellular networks provide high-speed service for large number of populations at low cost, satellite networks can provide the most comprehensive coverage for users than cannot be served by base stations (BSs). Thus the integrated terrestrial-satellite network may play an important role in future communications [4]. For the sake of spectrum efficiency, the technique of cognitive radio (CR), which allows dynamic spectrum access, was applied to terrestrial-satellite networks in [5]. In [6], the scenario of the hybrid satellite terrestrial relay network (HSTRN) was investigated, in which terrestrial relays were used to assist the transmission of the satellite.

In this paper, we propose an architecture of cloud based integrated terrestrial-satellite networks (CTSN), in which satellite and terrestrial networks that belong to the same operator cooperatively provide seamless coverage for users. In CTSN, both the satellite and RRHs are connected to the BBU at the cloud, and the computational signal processing procedures will be centralized at the cloud. Then, based on the delay constraints, we formulate the joint energy minimization and resource allocation problem of the whole system. By decomposing the problem into two subproblems, we finally obtain the optimal resource allocation strategies of power and computation resources.

2 SYSTEM MODEL

2.1 Scenario

Consider a cloud based integrated terrestrial-satellite network (CTSN) as show in Fig. 1, in which one satellite and L RRHs that belong to the same operator cooperatively provide seamless coverage for mobile users, and the resource pool at cloud acts as the integrated resource management and control center of the entire network. In CTSN, the satellite network and the terrestrial network share the same spectrum, and a reverse mode is considered in this paper, in which the downlink of the satellite and the uplink of the terrestrial network share the same spectrum. Considering satellite users are located in areas without coverage of terrestrial networks, the satellite users will not receive interference from terrestrial users. Thus the main interference in the network is the interference from the satellite to RRHs.

2.2 Transmission Model

With M antennas, the satellite provides service for M single-antenna users. The received SNR and capacity is

$$\gamma_{S,m} = \frac{|\mathbf{g}_{S,m}^H \boldsymbol{v}_m|^2 P_{S,m}}{\sigma_m^2}, C_{S,m} = \log_2(1+\gamma_{S,m}), \qquad (1)$$

where $\mathbf{g}_{S,m}$ is the channel vector, $\boldsymbol{v}_m$ is the zeroforcing beamforming (ZFBF) vector, $P_{S,m}$ is the transmit power, and σ_m^2 is the AWGN power. Let B be the bandwidth, the transmit delay and energy consumption of unit of data are

$$\tau_{S,m}^T = \frac{1}{BC_{S,m}}, E_{S,m}^T = \frac{1}{BC_{S,m}} P_{S,m}. \qquad (2)$$

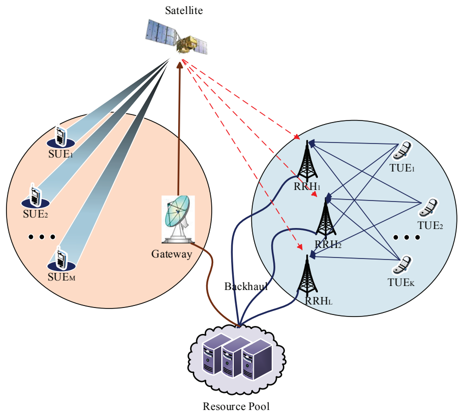

Figure 1. System model

In the terrestrial network, each RRH is equipped with N antennas and L RRHs cooperatively serve K single-antenna terrestrial users. The receive signal at RRH l is

$$\mathbf{y}_l=\sum_{k=1}^{K}\mathbf{h}_{l,k}\sqrt{P_{T,k}}s_{T,k}+\mathbf{G}_{T,l}^{H}\sum_{m=1}^{M}\boldsymbol{\nu}_m\sqrt{P_{S,m}}s_{S,m}+\mathbf{z}_l, \quad (3)$$

where $\mathbf{h}_{l,k}$ is the channel vector from user k to RRH l, $P_{T,k}$ is the transmit power, $s_{T,k}$ is the transmit signal, $\mathbf{G}_{T,l}=[\mathbf{g}_{T,l,1},\ldots,\mathbf{g}_{T,l,N}]$ is the channel matrix from the satellite to RRH l, and $\mathbf{z}_l$ is the AWGN. Then, all the received signals will be transmitted to the cloud for processing. Since the satellite signals are also processed at the cloud, the interference from the satellite can be canceled by subtracting the interference signal from the mixed signal based on channel state information (CSI). By executing ZFBF at the BBU for terrestrial users, the SNR and capacity of user k is

$$\gamma_{T,k}=\frac{|\boldsymbol{\omega}_k^H\mathbf{h}_k|^2P_{T,k}}{\sigma^2}, C_{T,k}=\log_2(1+\gamma_{T,k}), \quad (4)$$

where $\boldsymbol{\omega}_k$ is the beamforming vector and σ^2 is the AWGN power. With bandwidth B, the transmit delay and energy consumption of unit of data for user k are

$$\tau_{T,k}^{T}=\frac{1}{BC_{T,k}}, E_{T,k}^{T}=\frac{1}{BC_{T,k}}P_{T,k}. \quad (5)$$

2.3 Cloud Computation Model

Virtual machines (VMs) are generally used to represent the computation capacity of the cloud in [3]. We assume that there are total J homogeneous VMs with computation capacity f_{cp} (bps) and power consumption p_{cp}. Let $a_{S,m}\in[1,J], a_{T,k}\in[1,J]$ be the number of VMs assigned to satellite user m and terrestrial user k separately, and $\mathbf{a}=[\mathbf{a}_S^H,\mathbf{a}_T^H]^H$ be the set of assignment. Then the computation delay and energy consumption of unit of data for satellite user m are

$$\tau_{S,m}^{C}=\frac{1}{a_{S,m}f_{cp}}, E_{S,m}^{C}=\tau_{S,m}^{C}a_{S,m}p_{cp}=\frac{p_{cp}}{f_{cp}}. \quad (6)$$

Similarly, the computation delay and energy consumption of unit of data for terrestrial user k are

$$\tau_{T,k}^{C}=\frac{1}{a_{T,k}f_{cp}}, E_{T,k}^{C}=\tau_{T,k}^{C}a_{T,k}p_{cp}=\frac{p_{cp}}{f_{cp}}. \quad (7)$$

3 PROBLEM FORMULATION

In this paper, we define the delay constraint as the total time consumed of unit of data for transmission and signal processing at the cloud.

$$\tau_{S,m}=\tau_{S,m}^{T}+\tau_{S,m}^{C}, \tau_{T,k}=\tau_{T,k}^{T}+\tau_{T,k}^{C}. \quad (8)$$

Taking the delay constraint into account, we formulate the joint energy minimization and resource allocation problem for the operator as follows.

$$\min_{\mathbf{a}_S,\mathbf{a}_T,\mathbf{P}_S,\mathbf{P}_T}\sum_{m=1}^{M}(E_{S,m}^{C}+E_{S,m}^{T})+\sum_{k=1}^{K}E_{T,k}^{C} \quad (9)$$

$$\begin{aligned}
&C1:\sum_{m=1}^{M}a_{S,m}+\sum_{k=1}^{K}a_{T,k}\le J,\\
&C2: a_{S,m},a_{T,k}\ge 1, m=1,\ldots,M, k=1,\ldots,K,\\
&C3:\tau_{S,m}^{C}+\tau_{S,m}^{T}\le\tau_{S,m}, m=1,\ldots,M,\\
&C4:\tau_{T,k}^{C}+\tau_{T,k}^{T}\le\tau_{T,k}, k=1,\ldots,K,\\
&C5:\sum_{m=1}^{M}P_{S,m}\le P_{S,\max}, P_{S,m}\ge 0\\
&C6: P_{T,k}\le P_{T,\max}, P_{T,k}\ge 0, k=1,\ldots,K,
\end{aligned}$$

4 ENERGY EFFICIENT VM AND POWER ALLOCATION SCHEME

4.1 Problem Decomposition

From (6) and (7), we can see that the computation energy consumptions $E_{S,m}^{C}$ and $E_{T,k}^{C}$ are constant for unit of data, and thus the objective function of (9) is equal to minimizing the transmit energy consumption for satellite users.

$$\min_{\mathbf{a}_S,\mathbf{a}_T,\mathbf{P}_S,\mathbf{P}_T}\sum_{m=1}^{M}E_{S,m}^{T}=\sum_{m=1}^{M}\frac{P_{S,m}}{\log_2\left(1+\frac{|\mathbf{g}_{S,m}^{H}\boldsymbol{\nu}_m|^2P_{S,m}}{\sigma^2}\right)}. \quad (10)$$

Theorem 1 *The minimum transmit energy consumption for satellite users is achieved when the number of VMs allocated to satellite users is maximized.*

We can see that the objective function in (10) is only the function of $P_{S,m}$, and the constraints of satellite users and terrestrial users are independent except the maximum VM number constraint C1. Based on Theorem 1, the problem (10) can be decomposed into two subproblems:

$$\underline{Subproblem\ 1}:\ \min_{\mathbf{a}_T,\mathbf{P}_T}\sum_{k=1}^{K}a_{T,k} \quad (11)$$

$$C1:\tau_{T,k}^{C}+\tau_{T,k}^{T}\le\tau_{T,k}.$$

$$\underline{Subproblem\ 2}:\ \min_{\mathbf{a}_S,\mathbf{P}_S}\sum_{m=1}^{M}E_{S,m}^{T} \quad (12)$$

$$C1:\sum_{m=1}^{M}a_{S,m}=J-\sum_{k=1}^{K}a_{T,k}=J_S,$$

$$C2:\tau_{S,m}^{C}+\tau_{S,m}^{T}\le\tau_{S,m}.$$

4.2 Terrestrial Subproblem

We first solve the subproblem 1 to obtain the minimum number of VMs allocated to terrestrial users while satisfying the delay constraint. The constraint C1 can be transformed as

$$a_{T,k} \geq a^*_{T,k} = \frac{1}{f_{cp}} \frac{1}{\tau_{T,k} - \frac{1}{B\log_2(1+\frac{|\boldsymbol{\omega}_k^H \mathbf{h}_k|^2 P_{T,\max}}{\sigma^2})}}. \tag{13}$$

In order to minimize $a_{T,k}$, it is obvious that the transmit power of terrestrial users $P_{T,k}$ should be set as $P_{T,k} = P_{T,\max}$. Then, the minimum value of $a_{T,k}$ is

$$a_{T,k} = max\{1, \lceil a^*_{T,k} \rceil\}. \tag{14}$$

4.3 Satellite Subproblem

By solving subproblem 1, we now have obtained the maximum number of VMs that can be allocated to satellite users $J_S = J - \sum\limits_{k=1}^{K} a_{T,k}$.

Theorem 2 *The minimum transmit energy consumption for satellite users is achieved when the delay constraint of each satellite users is exactly satisfied.*

Based on Theorem 2, we have

$$\frac{1}{B\log_2(1+\frac{|\mathbf{g}_{S,m}^H \mathbf{v}_m|^2 P_{S,m}}{\sigma^2})} = \tau_{S,m} - \frac{1}{a_{S,m} f_{cp}}, m = 1, ..., M. \tag{15}$$

Once the VM allocation scheme is determined, the power allocation scheme can then be calculated that satisfies the delay constraint while taking the maximum power constraint into consideration.

Since each user is allocated at least one VM, the maximum energy consumption and the corresponding power allocation, when each user is only allocated one VM, are

$$E_S^T(0) = \sum_{m=1}^{M} E_{S,m}^T(0), P_S(0) = \sum_{m=1}^{M} P_{S,m}(0), \tag{16}$$

where $E_{S,m}^T(j)$ and $P_{S,m}(j)$ represent the energy consumption and power allocated for user m when j extra VMs are allocated to user m except the basic one. Then, the original problem can be transformed into the problem of allocating the extra $J_S^* = J_S - M$ VMs to all the M users. We use $E_{S,gain}^T(J_S^*)$ and$P_{S,gain}(J_S^*)$ to represent the the decrease of the energy and power compared with no extra VMs.

$$\begin{aligned} &E_{S,gain}^T(J_S^*) = E_S^T(0) - E_S^T(J_S^*) \qquad (17)\\ &= \sum_{m=1}^{M} \left[E_{S,m}^T(0) - E_{S,m}^T(J_{S,m}^*)\right] = \sum_{m=1}^{M} E_{S,m,gain}^T(J_{S,m}^*),\\ &P_{S,gain}(J_S^*) = P_S(0) - P_S(J_S^*)\\ &= \sum_{m=1}^{M} \left[P_{S,m}(0) - P_{S,m}(J_{S,m}^*)\right] = \sum_{m=1}^{M} P_{S,m,gain}(J_{S,m}^*), \end{aligned}$$

The allocation problem of the J_S^* extra VMs is actually equal to a transformed multidimensional knapsack problem [7]. Each user have multiple volumes from 0 to J_S^*, which means 0 to J_S^* extra VMs can be allocated to each user, and each volume corresponds to different energy gaining and power gaining. The objective is to put satellite users into the knapsack to maximize the energy gaining while satisfying the maximum volume constraint and the minimum power gaining constraint.

Since the maximum power of the satellite is $P_{S,max}$, the power constraint for $P_{S,gain}(J_S^*)$ is

$$P_{S,gain}(J_S^*) \geq P_{S,\min gain} = P_{S,\max} - P_S(0). \tag{18}$$

Since the recursive equation of knapsack problem can only be obtained when the constraints are discrete values, we quantize it by $\Delta P_S = \frac{P_{S,\max}}{D_P}$, where D_P is the quantization factor. Then the minimum power gaining is represented by $d_{\max} = \left\lceil \frac{P_{S,\min gain}}{\Delta P_S} \right\rceil$, and $d_m(j_m) = \left\lfloor \frac{P_{S,m,gain}(j_m)}{\Delta P_S} \right\rfloor$ is the power gaining of user m when allocate j_m VMs to user m. Let $E_{S,gain}^T(m,j,d)$ and $P_S(m,j,d)$ be the maximum energy gaining and corresponding power gaining when the first m users are used, j VMs are allocated, and the minimum power gaining is d. Then the recursive equation can be obtained as

$$\begin{aligned} E_{S,gain}^T(m,j,d) = \max \Big\{ &E_{S,gain}^T(m-1,j,d), \qquad (19)\\ &E_{S,gain}^T(m-1,j-1,d-d_m(1)) + E_{S,m,gain}^T(1),\\ &..., E_{S,gain}^T(m-1,j-j,d-d_m(j)) + E_{S,m,gain}^T(j) \Big\}. \end{aligned}$$

By calculating the three-dimension matrix $E_{S,gain}^T(m,j,d)$ from $m = 1$ to $m = M$, $j = 0$ to $j = J_S^*$, and $d = 0$ to $d = d_{max}$ based on (19), the maximum energy gaining can be eventually obtained as $E_{S,gain}^T(M,J_S^*,d_{max})$, and the minimum energy consumption can be calculated as

$$E_S^T(M,J_S^*,d_{max}) = E_S^T(0) - E_{S,gain}^T(M,J_S^*,d_{max}). \tag{20}$$

Then, the power allocation scheme can be obtained by (15).

5 Simulation Results

In this section, numerical results are now provided to evaluate the performance of the proposed strategies. The carrier frequency is set as 2 GHz and the bandwidth $B = 10$ MHz. Consider the satellite to be a LEO on the orbit of 1,000 km, and the parameters are set referring to [8]. Terrestrial users are randomly distributed in the system with the uniform maximum transmit power $P_{B,max} = 23$ dBm. The computation capacity of each VM is set as $\mu_m = 10^9$ cycle/s, and then we can obtain $f_{cp} = (8/1900) \times \mu_m$ (bps) and $p_{cp} = \alpha(\mu_m)^3$ [3], where $\alpha = 10^{-26}$.

Fig. 2 shows the energy consumption when different numbers of VMs are available, where we set $M = 4$, $N = 4$,

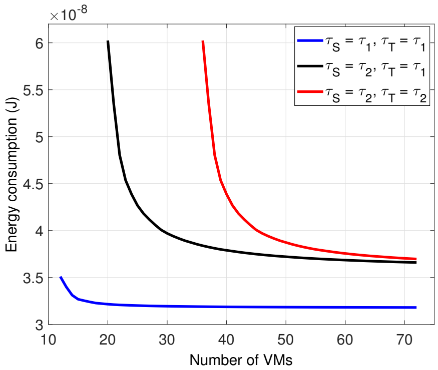

Figure 2. Energy consumption of different VMs.

$L = 4$, $K = 8$, and $\tau_1 = 3\tau_2 = 1.5/f_{cp}$. We can observe that the energy consumption will first decrease fast as the number of available VMs increases. For the case $\tau_S = \tau_T = \tau_1$, the energy consumed decreases by about 33.3% when the number of VMs increases from 20 to 30. Then, as the number of VMs continues to increase, the energy consumption will decrease more slowly. When the number of VMs continues to increase from 30 to 70, the energy consumed only decreases by about 8%. When τ_S changes from τ_1 to τ_2, the energy consumption will increase by about 14 % if enough VMs is available.

In Fig. 3, with $M = 4$, $N = 4$, $L = 4$, $K = 8$, $\tau_S = \tau_2$, and $\tau_T = \tau_1$, we compare the performance of the proposed optimal strategy with two other strategies. In the "Average strategy", VMs are allocated to all users averegly. In the "Suboptimal strategy", we first calculate the minimum number of VMs for terrestrial users based on (14), and then allocated VMs to satellite users averagely. We can observe that for different number of VMs, our proposed optimal strategy clearly outperforms the other two algorithms. Compared with the average strategy, our proposed strategy can save about 25% energy by allocating VMs and power more efficiently among users, while the low-complexity suboptimal strategy outperforms the average strategy by about 20%. However, we can observe that there is still about 6% performance loss for the suboptimal strategy.

6 Conclusion

In this paper, we proposed a general framework of the cloud based integrated terrestrial-satellite network. Taking the delay constraint of users in to account, we formulated the minimum energy problem of power and VM allocation for the operator, which was then decomposed into two subproblems. By transforming the VM assigning problem into a multidimensional knapsack problem, we eventually obtained the optimal resource allocation strategies for the operator. Simulation results showed that the proposed integrated networks and resource allocation strategies can achieve good performance. Our proposed optimal strategies can save about 25% energy by allocating VMs and power more efficiently among users.

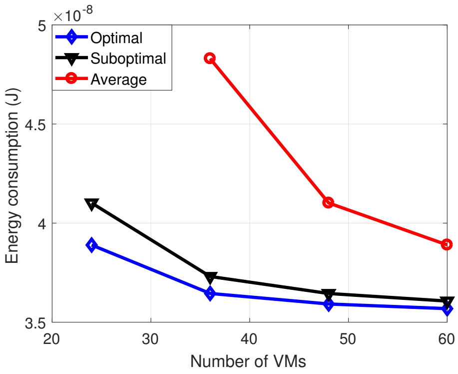

Figure 3. Performance of different strategies.

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