DT-Aided Resource Management in Spectrum Sharing Integrated Satellite-Terrestrial Networks

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***Abstract*—The integrated satellite-terrestrial networks (ISTNs) through spectrum sharing have emerged as a promising solution to improve spectral efficiency and meet increasing wireless demand. However, this coexistence introduces significant challenges, including inter-system interference (ISI) and the low Earth orbit satellite (LSat) movements. To capture the actual environment for resource management, we propose a time-varying digital twin (DT)-aided framework for ISTNs incorporating 3D map that enables joint optimization of bandwidth (BW) allocation, traffic steering, and resource allocation, and aims to minimize congestion. The problem is formulated as a mixed-integer nonlinear programming (MINLP), addressed through a two-phase algorithm based on successive convex approximation (SCA) and compressed sensing approaches. Numerical results demonstrate the proposed method's superior performance in queue length minimization compared to benchmarks.**

I. Introduction

Recently, sharing the same radio frequency band (RFB) between terrestrial network (TN) and non-terrestrial networks (NTN) systems has become a promising solution to enhance spectral efficiency and support the growing demand for wireless connectivity [1]. However, sharing the same RFBs introduces the critical ISI issue. Additionally, the movements of users (UEs) and LSat further introduce dynamics to the systems [2], [3]. Hence, optimizing systems to manage the ISI issue and terminal movement poses significant challenges, especially in complex environments such as urban areas [4].

The spectrum sharing ISTNs has been studied in the literature such as [5]–[10]. Particularly, in [5], [6], the performance analysis is investigated by using the stochastic geometry approach. In [7], [8], the snapshot resource management in different scenarios are studied. However, the consideration of the snapshot model in these works struggles to capture the dynamic systems in ISTNs. Subsequently, the spectrum sharing problem is studied in [9], [10] limited to the system level. Almost all existing works rely on the statistical channel model, which is challenging to capture actual environments.

In this work, we study the time-varying DT-aided ISTNs where TN and NTN systems share the same RFB. We aim to optimize BW allocation, traffic steering, UE and resource block (RB) assignment, and power control under the service constraint to minimize the congestion, i.e., queue length minimization. The underlying MINLP problem is challenging to solve. Additionally, the problem requires information of channel gain and arrival traffic of the upcoming time cycle (TC) which further poses challenge in solving. To assist resource management, we utilize a DT model with the 3D map to capture the system. Furthermore, we propose a two-phase algorithm based on the SCA technique. First, the problem for a TC is solved based on the predicted information from the DT model. Subsequently, the power control is re-optimized based on the instant estimated channel and initial point provided by the first algorithm's outcome. The greedy algorithm is further proposed for comparison purposes. The numerical result shows the effectiveness in terms of queue length minimization.

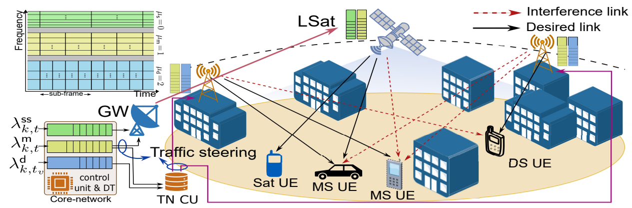

Fig. 1: System model.

II. System Model

We consider the downlink (DL) ISTNs including N access points (APs), one LSat, and K users described in Fig. 1. Let $\mathcal{N} = \{1, \ldots, N\}$ and $\mathcal{U} = \{1, \ldots, K\}$, AP_n, and UE_k denote the sets of APs and UEs, the n–th AP and k–th UE, where index $n = 0$ indicates the LSat, respectively. The user set is divided into three sets using delay-sensitive (DS), satellite (SS) and mobile (MS) services denoted by $\mathcal{U}^{\mathsf{d}}$, $\mathcal{U}^{\mathsf{s}}$, and $\mathcal{U}^{\mathsf{m}}$ served by APs, LSat, and both, respectively. For convenience, let $\mathcal{S}^{\mathsf{tn}} = \{\mathsf{d}, \mathsf{m}\}$, $\mathcal{S}^{\mathsf{sn}} = \{\mathsf{m}, \mathsf{s}\}$, and $\mathcal{S} = \{\mathsf{d}, \mathsf{s}, \mathsf{m}\}$ be the service sets. We consider systems in N_{cy} TCs, each TC indexed by c consists of N^{tf} time-frame (TF). We assume that the ISTNs operate in the shared RFB with the BW of B which can be dynamically allocated to services, TNs, and satellite networks (SNs) over TCs. Particularly, the entire BW is divided into three bandwidth parts (BWPs) used for DS, MS, and SS services, respectively. Furthermore, we assume that the OFDMA and 5G NR frameworks are utilized where numerologies μ_{x} are used for BWPs $\mathsf{x} \in \mathcal{S}$ with $\mu_{\mathsf{s}} = 0, \mu_{\mathsf{m}} = 1$ and $\mu_{\mathsf{d}} = 2$ [11], respectively. Each TF consists of 10 sub-frames (SFs). Assuming that TNs and SNs operate in TDD and FDD modes, TNs use $N^{\mathsf{tn,dl}}_{\mathsf{sf}}$ beginning SFs while SNs use 10 SFs for DL in each TF. The radio resource is divided into a grid of RBs where the RB size (duration and BW) is scaled according to numerology μ with the parameters described in Table. I. To avoid the inter-numerology-interference, we assume that there are guard bands with fixed BWs of $B^{\mathsf{sm}}_{\mathsf{G}} = w_{\mathsf{s}}$ and $B^{\mathsf{md}}_{\mathsf{G}} = w_{\mathsf{m}}$ between BWPs $\mathsf{s} - \mathsf{m}$ and $\mathsf{m} - \mathsf{d}$, respectively. To describe the BW allocation, we introduce the binary variable $\boldsymbol{b}_c \triangleq \{b^{\mathsf{x}}_{f^{\mathsf{x}},c} | \forall f^{\mathsf{x}} \in \mathcal{F}^{\mathsf{x}}, \mathsf{x} \in \mathcal{S}\}$ where $b^{\mathsf{x}}_{f^{\mathsf{x}},c} = 1$ if sub-band (SB) f^{x} service x used at TC c and = 0 in otherwise. To ensure the non-overlap between BWPs, the continuity in BWPs, and maximum BW, one needs to hold constraints

$$(C1):\ b^{\mathsf{d}}_{f^{\mathsf{d}},c}+\sum_{i=1}^{\bar{Q}^{\mathsf{d}}_{\mathsf{m}}(f^{\mathsf{d}}+0.5)}b^{\mathsf{m}}_{i,c}+\sum_{j=1}^{\bar{Q}^{\mathsf{d}}_{\mathsf{s}}(f^{\mathsf{d}}+0.5)}b^{\mathsf{s}}_{j,c}\leq 1,\ \forall f^{\mathsf{d}},c,$$

$$(C2):\ b^{\mathsf{m}}_{f^{\mathsf{m}},c}+\sum_{i=1}^{\bar{Q}^{\mathsf{m}}_{\mathsf{s}}(f^{\mathsf{m}}+0.5)}b^{\mathsf{s}}_{i,c}\leq 1,\ \forall f^{\mathsf{m}},\forall c,$$

$$(C3):\ \sum_{\mathsf{x}\in\{\mathsf{d},\mathsf{m},\mathsf{s}\}}w_{\mathsf{x}}\sum_{\forall f^{\mathsf{x}}\in\mathcal{F}^{\mathsf{x}}}b^{\mathsf{x}}_{f^{\mathsf{x}},c}+B^{\mathsf{sm}}_{\mathsf{G}}+B^{\mathsf{md}}_{\mathsf{G}}\leq B,\ \forall c.$$

A. Digital-Twin Model

The DT model includes the replication of features and relevant information of UEs, APs, LSats, and environments. In cell n, the DT model of environment in its area and AP_n are $\mathsf{DT}^{\mathsf{env}}_n=\{\mathsf{map}_n\}$, $\mathsf{DT}^{\mathsf{ap}}_n=\{\boldsymbol{u}^{\mathsf{ap}}_n\}$, $\forall n\in\mathcal{N}$, where map_n and $\boldsymbol{u}^{\mathsf{ap}}_n$ are 3D map of cell n area AP_n's position [12], [13]. The DTs of $\mathsf{UE_k}$ and the LSat at TF t are modeled as $\mathsf{DT}^{\mathsf{ue}}_{k,t}=\{\hat{\boldsymbol{u}}^{\mathsf{ue}}_{k,t},\hat{\lambda}^{\mathsf{x}}_{k,t}\},\forall k\in\mathcal{U}^{\mathsf{x}},\mathsf{x}\in\mathcal{S}$, $\mathsf{DT}^{\mathsf{sat}}_t=\{\boldsymbol{u}^{\mathsf{sat}}_t\}$, where $\hat{\boldsymbol{u}}^{\mathsf{ue}}_{k,t}$, $\boldsymbol{u}^{\mathsf{sat}}_t$ and $\hat{\lambda}^{\mathsf{x}}_{k,t}$ are the UE_k, LSat positions and UE_k arrival rate in the DT model obtained by the updated real information.

B. Channel Model

Let $\tilde{h}^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}$ be the channel coefficient between AP_n and UE_k over SB f^{x} in BWP $\mathsf{x}\in\mathcal{S}^{\mathsf{tn}}$ at TS t^{x}_s. Regarding the LSat-UE links, let $\tilde{g}^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{m,k}$ be the channel coefficient between LSat_m and UE_k over SB f^{x} in BWP $\mathsf{x}\in\mathcal{S}^{\mathsf{sn}}$ at TS t^{x}_s. The channels of AP-UE and LSat-UE links are modeled based on the Rician channel model and ray-tracing (RT) mechanism. For simplicity, let's us omit the index x in the RB's index in this section, channels coefficients $\tilde{h}^{f,t_s}_{n,k}$ and $\tilde{g}^{f,t_s}_{m,k}$ are modeled as $\tilde{h}^{f,t_s}_{n,k}=\sqrt{\mathsf{PL}^{f,t_s}_{n,k}}(\sqrt{\frac{\tilde{K}}{\tilde{K}+1}}\tilde{h}^{\mathsf{los},f,t_s}_{n,k}+\sqrt{\frac{1}{\tilde{K}+1}}\tilde{h}^{\mathsf{nlos},f,t_s}_{n,k})$, $\tilde{g}^{f,t_s}_{k}=\sqrt{\mathsf{PL}^{f,t_s}_{k}}(\sqrt{\frac{\tilde{K}}{\tilde{K}+1}}\tilde{g}^{\mathsf{los},f,t_s}_{k}+\sqrt{\frac{1}{\tilde{K}+1}}\tilde{g}^{\mathsf{nlos},f,t_s}_{k})$, wherein $\tilde{K}$ is the K-factor, $\mathsf{PL}^{f,t_s}_{n,k}$, $\tilde{h}^{\mathsf{los},f,t_s}_{n,k}$, $\tilde{h}^{\mathsf{nlos},f,t_s}_{n,k}$, PL^{f,t_s}_{k}, $\tilde{g}^{\mathsf{los},f,t_s}_{k}$, and $\tilde{g}^{\mathsf{nlos},f,t_s}_{k}$ indicate the path-loss, line-of-sight (LoS) and non-line-of-sight (NLoS) components of $\mathsf{AP}_n-\mathsf{UE}_k$ and $\mathsf{LSat}-\mathsf{UE}_k$ links at the corresponding frequency and time, respectively.

To reflect the environment features in considered area, the RT mechanism is utilized with APs, LSat, and UEs positions and 3D map of considered areas in generating the channel [12], [13]. Since the 3D map data is incomplete for all objects in the environment, the RT mechanism cannot compute the full channel paths. Hence, the NLoS components are further modeled as $\tilde{h}^{\mathsf{nlos},f,t_s}_{n,k}=\sqrt{\xi}\bar{h}^{\mathsf{nlos},f,t_s}_{n,k}+\sqrt{(1-\xi)}\delta^{f,t_s}_{n,k}$ and $\tilde{g}^{\mathsf{nlos},f,t_s}_{k}=\sqrt{\xi}\bar{g}^{\mathsf{nlos},f,t_s}_{k}+\sqrt{(1-\xi)}\delta^{f,t_s}_{k}$, where $\bar{h}^{\mathsf{nlos},f,t_s}_{n,k}$ and $\bar{g}^{\mathsf{nlos},f,t_s}_{k}$ indicate the NLoS components identified by the RT mechanism while $\delta^{f,t_s}_{n,k}$ and δ^{f,t_s}_{k} indicate the NLoS components resulting from objects absent in the 3D map data. Hence, they can be modeled as complex normal random variables with zero mean and unit variance. $\xi\in(0,1)$ is the factor wherein $\xi=1$ indicates that the NLoS component is deterministic while $\xi=0$ means the NLoS component follows the traditional Rician model.

C. Transmission Model

1) Association Model: Let $\boldsymbol{\alpha}=[\alpha^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}]$ where $\alpha^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}=1$ if UE_k served by AP_n over $\mathsf{RB}(f^{\mathsf{x}},t^{\mathsf{x}}_s)$ and $s\leq N^{\mathsf{tn,dl}}_{\mathsf{sf}}N^{\mathsf{sf,x}}_{\mathsf{ts}}$, and $=0$ otherwise. It is aligned with BW allocation as

	Index	Duration (ms)
Frame (TF) Sub-frame (SF) Time-slot (TS) service x	$t\in\mathcal{T}^{\mathsf{tf}}_c\triangleq\{(c-1)N_{\mathsf{tf}}+1,\ldots,cN_{\mathsf{tf}}\}$ $t_v\in\mathcal{T}^{\mathsf{sf}}_t\triangleq\{10(t-1)+v,v\in\{1,\ldots,10\}\}$ $t^{\mathsf{x}}_s\in\mathcal{T}^{\mathsf{sf,x}}_{t_v}\triangleq\{(t_v-1)N^{\mathsf{sf,x}}_{\mathsf{ts}}+1,\ldots,t_vN^{\mathsf{sf,x}}_{\mathsf{ts}}\}$ $\subset\mathcal{T}^{\mathsf{x}}_t\triangleq\{(t-1)N^{\mathsf{x}}_{\mathsf{ts}}+1,\ldots,tN^{\mathsf{x}}_{\mathsf{ts}}\}$	$T_{\mathsf{f}}=10$ $T_{\mathsf{sf}}=1$ $T_{\mathsf{x}}=2^{-\mu_{\mathsf{x}}}$
N_{tf}: #TF/cycle, $N^{\mathsf{x}}_{\mathsf{ts}}$: #TS/TF, $N^{\mathsf{sf,x}}_{\mathsf{ts}}$: #TS/SF, $N_{\mathsf{sf}}=10$ SFs/TF $\mathcal{T}^{\mathsf{tf}}_c=\{(c-1)N_{\mathsf{tf}}+1,\ldots,cN_{\mathsf{tf}}\}$: TF set in TC c $\mathcal{T}^{\mathsf{ts,x}}_c=\{t^{\mathsf{x}}_s\vert\forall t^{\mathsf{x}}_s\in\mathcal{T}^{\mathsf{x}}_t,\forall t\in\mathcal{T}^{\mathsf{tf}}_c\}$: TS set in TC c		
	Index	Bandwidth (kHz)
Sub-band (SB) service x	$f^{\mathsf{x}}\in\mathcal{F}^{\mathsf{x}}\triangleq\{1,\ldots,F^{\mathsf{x}}\}$	$w_{\mathsf{x}}=2^{\mu_{\mathsf{x}}}\times 180$
$F^{\mathsf{x}}=\lfloor B/w_{\mathsf{x}}\rfloor$: Num. SBs service x, $\bar{Q}^{\mathsf{x}}_{\mathsf{x}'}=2^{\mu_{\mathsf{x}}-\mu_{\mathsf{x}'}}$: RB BW ratio,		

TABLE I: Parameter of the resource block grid.

$$(C4):\alpha^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}\leq b^{\mathsf{x}}_{f^{\mathsf{x}},c},\forall(k,f^{\mathsf{x}},t^{\mathsf{s}}_{x})\in\mathcal{U}^{\mathsf{x}}\times\mathcal{F}^{\mathsf{x}}\times\mathcal{T}^{\mathsf{ts,x}}_c,\mathsf{x}\in\mathcal{S}^{\mathsf{tn}},\forall n,c.$$

To ensure the orthogonality at each AP, one assumes that each RB of each AP can be assigned to at most one UE, as follows

$$(C5):\sum_{\forall k}\alpha^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}\leq 1,\ \forall(f^{\mathsf{x}},t^{\mathsf{x}}_s)\in\mathcal{F}^{\mathsf{x}}\times\mathcal{T}^{\mathsf{ts,x}}_c,\mathsf{x}\in\mathcal{S}^{\mathsf{tn}},\forall n,c.$$

Regarding multi-connectivity, each UE^{d} can be served by multiple APs at each TS via different RBs, as follows

$$(C6):\sum_{\forall n}\alpha^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}\leq 1,\ \forall k\in\mathcal{U}^{\mathsf{d}},\forall(f^{\mathsf{d}},t^{\mathsf{d}}_s)\in\mathcal{F}^{\mathsf{d}}\times\mathcal{T}^{\mathsf{ts,d}}_c,\forall c.$$

Regarding LSat-UE association, we introduce a variable $\boldsymbol{\beta}=[\beta^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_k]$ where $\beta^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_k=1$ if UE_k served by LSat over $\mathsf{RB}(f^{\mathsf{x}},t^{\mathsf{x}}_s)$, and $=0$ otherwise. Similar to the AP-UE association, the LSat-UE association must satisfy

$$(C7):\ \beta^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_k\leq b^{\mathsf{x}}_{f^{\mathsf{x}},c},\forall(k,f^{\mathsf{x}},t^{\mathsf{x}}_x)\in\mathcal{U}^{\mathsf{x}}\times\mathcal{F}^{\mathsf{x}}\times\mathcal{T}^{\mathsf{ts,x}}_c,\mathsf{x}\in\mathcal{S}^{\mathsf{sn}},\forall c.$$

The orthogonality between UEs served by the LSat is

$$(C8):\sum_{\forall k}\beta^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_k\leq 1,\ \forall(f^{\mathsf{x}},t^{\mathsf{x}}_s)\in\mathcal{F}^{\mathsf{x}}\times\mathcal{T}^{\mathsf{ts,x}}_c,\mathsf{x}\in\mathcal{S}^{\mathsf{sn}},\forall c.$$

Additionally, we assume that UEs using MS services can be served by both the BSs and LSat at the same time via different RBs in BWP m, which yields the constraint

$$(C9):\ \sum_{\forall n}\alpha^{f^{\mathsf{m}},t^{\mathsf{m}}_s}_{n,k}+\beta^{f^{\mathsf{m}},t^{\mathsf{m}}_s}_k\leq 1,\ \forall k\in\mathcal{U}^{m},\forall(f^{\mathsf{m}},t^{\mathsf{m}}_s),\forall c.$$

2) Transmission over BWP d*:* This BWP is utilized only by APs to serve DS UEs. The $\mathsf{UE}^{\mathsf{d}}_k$ received signal over $\mathsf{RB}(f^{\mathsf{d}},t^{\mathsf{d}}_s)$ is expressed as $y^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_k=f^{\mathsf{rx,tn,d}}_k(\boldsymbol{p}_t,\boldsymbol{\alpha}_t,\boldsymbol{x}_t)+\varsigma^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_k$, where $f^{\mathsf{rx,tn,x}}_k(\boldsymbol{p}_t,\boldsymbol{\alpha}_t,\boldsymbol{x}_t)=\sum_{\forall i}\sum_{\forall j}\sqrt{\alpha^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{i,j}p^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{i,j}}\tilde{h}^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{i,k}x^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{i,j}$, $p^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}$ and $x^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}$ are the transmission power and symbol from AP_n to UE_k over $\mathsf{RB}(f^{\mathsf{d}},t^{\mathsf{d}}_s)$. $\varsigma^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_k$ is the additive Gaussian noise at UE_k. Hence, the corresponding signal-to-interference-plus-noise-ratio (SINR) is expressed as

$$\gamma^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t)=\alpha^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}p^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}h^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}/(\Psi^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t)+\sigma^2_{\mathsf{d},k}),\quad(1)$$

with $\boldsymbol{p}_t\triangleq\{p^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}\vert\forall n,\forall f^{\mathsf{x}}_n,\forall k\in\mathcal{U}^{\mathsf{x}},\forall t^{\mathsf{x}}_s\in\mathcal{T}^{\mathsf{x}}_t,\mathsf{x}\in\{\mathsf{d},\mathsf{m}\}\}$, $\boldsymbol{\alpha}_t\triangleq\{\alpha^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}\vert\forall n,\forall f^{\mathsf{x}}_n,\forall k\in\mathcal{U}^{\mathsf{x}},\forall t^{\mathsf{x}}_s\in\mathcal{T}^{\mathsf{x}}_t,\mathsf{x}\in\mathcal{S}^{\mathsf{tn}}\}$, and $h^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}=\vert\tilde{h}^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}\vert^2$. $\Psi^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{n,k}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t)=\sum_{\forall i\neq n}\sum_{\forall j}\alpha^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{i,j}p^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{i,j}h^{f^{\mathsf{x}},t^{\mathsf{x}}_s}_{i,k}$ is the ICI power at $\mathsf{UE}^{\mathsf{x}}_k$. Due to the delay requirement of the DS services, we assume that DS data is transmitted within each SF and the short packet framework is used for the transmission of DS services. Hence, according to [14], the aggregated achievable rate of $\mathsf{UE}^{\mathsf{d}}_k$ served by AP_n at SF t^{d}_v can be expressed as $R^{\mathsf{d},t^{\mathsf{d}}_v}_{n,k}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t)=w_{\mathsf{d}}\sum_{\forall f^{\mathsf{d}}\in\mathcal{F}^{\mathsf{d}}}\sum_{\forall t^{\mathsf{d}}_s\in\mathcal{T}^{\mathsf{sf,d}}_{t_v}}\Big(\ln(1+\gamma^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t))-\alpha^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}\sqrt{V^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}}Q^{-1}(P_\epsilon)/\sqrt{\sum_{\forall f^{\mathsf{d}}\in\mathcal{F}^{\mathsf{d}}}\sum_{\forall t^{\mathsf{d}}_s\in\mathcal{T}^{\mathsf{sf,d}}_{t_v}}\alpha^{f^{\mathsf{d}},t^{\mathsf{d}}_s}_{n,k}\tau_{\mathsf{d}}w_{\mathsf{d}}}\Big)$, wherein

$V_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}} = 1-(1+\gamma_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t))^{-2}$, $Q^{-1}(\cdot)$ and P_ϵ are the channel dispersion, the inverse of the Q-function, and the error probability. The channel dispersion can be approximated as $V_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}} \approx 1$ for a sufficiently high $\gamma_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}(\boldsymbol{p}^{\mathsf{a}},\boldsymbol{\alpha}_t) \geq \gamma_0^{\mathsf{d}}$ with $\gamma_0^{\mathsf{d}} \geq 5$ dB [15]. To guarantee the channel dispersion approximation, we consider constraint

$$(C10): \quad \gamma_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t) \geq \alpha_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}\gamma_0^{\mathsf{d}},\ \forall(n,k)\in\mathcal{N}\times\mathcal{U}^{\mathsf{d}}.$$

Subsequently, let $\chi_{\mathsf{d}} = \sqrt{w_{\mathsf{d}}}\sqrt{V}Q^{-1}(P_\epsilon)/\sqrt{\tau_{\mathsf{d}}}$ and $V \approx V_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}} \approx 1$, the achievable rate $R_{n,k}^{\mathsf{d},t_v^{\mathsf{d}}}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t) = w_{\mathsf{d}}\sum_{\forall f^{\mathsf{d}}\in\mathcal{F}^{\mathsf{d}}}\sum_{\forall t_s^{\mathsf{d}}\in\mathcal{T}_{t_v}^{\mathsf{sf,d}}}\ln(1+\gamma_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t)) - \chi_{\mathsf{d}}\sqrt{\sum_{\forall f^{\mathsf{d}}\in\mathcal{F}^{\mathsf{d}}}\sum_{\forall t_s^{\mathsf{d}}\in\mathcal{T}_{t_v}^{\mathsf{sf,d}}}\alpha_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}}$.

3) Transmission over BWP m*:* In this BWP, UEs can be served by APs and the LSat. First, the received signal at $\mathsf{UE}_k^{\mathsf{m}}$ over $\mathsf{RB}(f^{\mathsf{m}},t_s^{\mathsf{m}})$ of $\mathsf{BWP}_t^{\mathsf{m}}$ can be expressed as

$$y_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}} = f_k^{\mathsf{rx,tn,m}}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t,\boldsymbol{x}_t) + \varsigma_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}} + f_k^{\mathsf{rx,sn,m}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t,\boldsymbol{x}_t).$$

with $f_k^{\mathsf{rx,sn,x}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t,\boldsymbol{x}_t) = \sum_{\forall j}\sqrt{\beta_j^{f^{\mathsf{m}},t_s^{\mathsf{m}}}P_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}}}\tilde{g}_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}}x_j^{f^{\mathsf{m}},t_s^{\mathsf{m}}}$. Assuming that $\mathsf{UE}_k^{\mathsf{m}}$ is served by AP_n, the SINR is written as

$$\gamma_{n,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t) = \frac{\alpha_{n,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}p_{n,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}h_{n,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}}{\Psi_{n,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t) + \Theta_k^{\mathsf{a},f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t) + \sigma_{\mathsf{m},k}^2},$$

and $\Theta_k^{\mathsf{a},f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t) = \sum_{\forall k'}\beta_{k'}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}P_{k'}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}g_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}}$ is the ISI from the LSat, where $P_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}}$ is the transmit power from the LSat to UE_k over $\mathsf{RB}(f^{\mathsf{x}},t_s^{\mathsf{x}})$ of BWP x, $\boldsymbol{P}_t \triangleq \{P_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}}|\forall f^{\mathsf{x}},\forall k\in\mathcal{U}^{\mathsf{x}},\forall t_s^{\mathsf{x}}\in\mathcal{T}_t^{\mathsf{x}},\mathsf{x}\in\{\mathsf{m},\mathsf{s}\}\}$, $\boldsymbol{\beta}_t \triangleq \{\beta_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}}|\forall f^{\mathsf{x}},\forall k\in\mathcal{U}^{\mathsf{x}},\forall t_s^{\mathsf{x}}\in\mathcal{T}_t^{\mathsf{x}},\mathsf{x}\in\{\mathsf{m},\mathsf{s}\}\}$, and $g_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}} = |\tilde{g}_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}}|^2$. The achievable rate from AP_n to $\mathsf{UE}_k^{\mathsf{m}}$ over $\mathsf{RB}(f^{\mathsf{m}},t_s^{\mathsf{m}})$ and TS t_s^{m} is

$$R_{n,k}^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t) = w_{\mathsf{m}}\ln\Big(1+\gamma_{n,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t)\Big), \quad (2a)$$

$$R_{n,k}^{\mathsf{m},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t) = \sum_{\forall f^{\mathsf{m}}\in\mathcal{F}^{\mathsf{m}}}R_{n,k}^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t). \quad (2b)$$

Subsequently, assuming that $\mathsf{UE}_k^{\mathsf{m}}$ is served by the LSat over $\mathsf{RB}(f^{\mathsf{m}},t_s^{\mathsf{m}})$ of $\mathsf{BWP}_t^{\mathsf{m}}$, the corresponding SINR is given as

$$\gamma_{0,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t) = \frac{\beta_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}}P_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}}g_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}}}{\Theta_k^{\mathsf{s},f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t) + \sigma_{\mathsf{m},k}^2},$$

where $\Theta_k^{\mathsf{s},f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{\alpha}_t) = \sum_{\forall n}\sum_{\forall k'}\alpha_{n,k'}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}p_{n,k'}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}h_{n,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}}$ is the ISI caused by APs to $\mathsf{UE}_k^{\mathsf{m}}$ served by SN systems. Therefore, the corresponding achievable rate of $\mathsf{UE}_k^{\mathsf{m}}$ can be given as

$$R_{0,k}^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t) = w_{\mathsf{m}}\ln\Big(1+\gamma_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t)\Big), \quad (3a)$$

$$R_{0,k}^{\mathsf{m},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t) = \sum_{\forall f^{\mathsf{m}}\in\mathcal{F}^{\mathsf{m}}}R_{\mathsf{s},k}^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}(\boldsymbol{p}_t,\boldsymbol{P}_t,\boldsymbol{\alpha}_t,\boldsymbol{\beta}_t). \quad (3b)$$

4) Transmission over BWP s*:* In this BWP, UEs using SS services are served by the LSat. Assuming that $\mathsf{UE}_k^{\mathsf{s}}$ is served by the LSat over $\mathsf{RB}(f^{\mathsf{s}},t_s^{\mathsf{s}})$ of $\mathsf{BWP}_t^{\mathsf{s}}$, its SNR can be expressed as $\gamma_{0,k}^{f^{\mathsf{s}},t_s^{\mathsf{s}}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t) = \beta_k^{f^{\mathsf{s}},t_s^{\mathsf{s}}}P_k^{f^{\mathsf{s}},t_s^{\mathsf{s}}}g_k^{f^{\mathsf{s}},t_s^{\mathsf{s}}}/\sigma_{\mathsf{s},k}^2$. The corresponding achievable rate at $\mathsf{UE}_k^{\mathsf{s}}$ can be given as $R_{0,k}^{\mathsf{s},f^{\mathsf{s}},t_s^{\mathsf{s}}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t) = w_{\mathsf{s}}\ln\Big(1+\gamma_{0,k}^{f^{\mathsf{s}},t_s^{\mathsf{s}}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t)\Big)$.

Therefore, the aggregated rate of $\mathsf{UE}_k^{\mathsf{s}}$ at TS t_s^{s} served by the LSat and TF t can be computed as

$$R_{0,k}^{\mathsf{s},t_s^{\mathsf{s}}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t) = \sum_{\forall f^{\mathsf{s}}\in\mathcal{F}^{\mathsf{s}}}R_{0,k}^{\mathsf{s},f^{\mathsf{s}},t_s^{\mathsf{s}}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t), \quad (4a)$$

$$R_{0,k}^{\mathsf{s},t}(\boldsymbol{P}_t,\boldsymbol{\beta}_t) = \sum_{\substack{\forall f^{\mathsf{s}}\in\mathcal{F}^{\mathsf{s}}\\ \forall t_s^{\mathsf{s}}\in\mathcal{T}_t^{\mathsf{s}}}}R_{0,k}^{\mathsf{s},f^{\mathsf{s}},t_s^{\mathsf{s}}}(\boldsymbol{P}_t,\boldsymbol{\beta}_t). \quad (4b)$$

To ensure the total transmit power at APs and the LSat not exceeding the transmit power budget, it must satisfy

$$(C11): \sum_{\forall k}\sum_{\mathsf{x}\in\{\mathsf{d},\mathsf{m}\}}\sum_{\forall f^{\mathsf{x}}\in\mathcal{F}^{\mathsf{x}}}p_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}} \leq p_n^{\mathsf{max}},\forall(n,t_s^{\mathsf{x}}),$$

$$(C12): \sum_{\forall k}\sum_{\mathsf{x}\in\{\mathsf{m},\mathsf{s}\}}\sum_{\forall f^{\mathsf{x}}\in\mathcal{F}^{\mathsf{x}}}P_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}} \leq P^{\mathsf{max}},\forall(m,t_s^{\mathsf{x}}).$$

5) Traffic and Queuing Model: We assume that there are K traffic flows corresponding to K UEs, and the data arrival at each time instance of services m and s will be served at the next TF while that of service d will be served at the next SF. Furthermore, one assumes that the arrival data of DS, MS, and SS services follows the Poisson distribution with means $\bar{\lambda}^{\mathsf{d}}$, $\bar{\lambda}^{\mathsf{m}}$, and $\bar{\lambda}^{\mathsf{s}}$, respectively. Besides, the DS and SS traffic flows at the core network (CN) are routed to the TN and SN systems, respectively, while the MS traffic flows are steered from the CN to TN and SN systems based on the traffic steering scheduler. We assume that the traffic steering decision is made for each TC. First, we introduce the flow-spit decision variable for the MS traffic at the core network $\boldsymbol{\omega}_c^{\mathsf{cn}} = [\omega_{k,c}^{\mathsf{cn}}],\forall k\in\mathcal{U}^{\mathsf{m}}$, wherein $\omega_{k,c}^{\mathsf{cn}}\in[0,1]$ and $(1-\omega_{k,c}^{\mathsf{cn}})$ are the portions of $\mathsf{UE}_k^{\mathsf{m}}$'s traffic which are steered to TN and SN systems during TC c, respectively. Besides, TNs have multiple APs while SNs have one LSat. Hence, the traffic flows at the TN CU are steered to APs. Herein, we introduce the flow-spit decision variables in TNs $\boldsymbol{\omega}_c^{\mathsf{x}} = [\omega_{n,k,c}^{\mathsf{x}}],\forall(n,k)\in(\mathcal{N}\times\mathcal{U}^{\mathsf{x}}),\mathsf{x}\in\mathcal{S}^{\mathsf{tn}}$ wherein $\omega_{n,k,c}^{\mathsf{x}}\in[0,1]$ indicates the flow split portion of service $\mathsf{x}\in\mathcal{S}^{\mathsf{tn}}$ from the TN CU to $\mathsf{AP_n}$ at TC c. Besides, the integrity of traffic flows is ensured by constraints

$$(C13): \sum_{\forall n\in\mathcal{N}}\omega_{n,k,c}^{\mathsf{x}} = 1,\forall k\in\mathcal{U}^{\mathsf{x}},\mathsf{x}\in\{\mathsf{d},\mathsf{m}\},\forall c.$$

Subsequently, the data arrival of the DS, MS, and DS services of UEs at AP_n and the LSat are expressed as

$$\lambda_{n,k,t_v}^{\mathsf{d}} = \omega_{n,k,c}^{\mathsf{d}}\lambda_{k,t_v}^{\mathsf{d}},\quad \lambda_{n,k,t}^{\mathsf{m}} = \omega_{k,c}^{\mathsf{cn}}\omega_{n,k,c}^{\mathsf{m}}\lambda_{k,t}^{\mathsf{m}}, \quad (5a)$$

$$\lambda_{0,k,t}^{\mathsf{m}} = (1-\omega_{k,c}^{\mathsf{cn}})\lambda_{k,t}^{\mathsf{m}},\quad \lambda_{0,k,t}^{\mathsf{s}} = \lambda_{k,t}^{\mathsf{s}}. \quad (5b)$$

Regarding the DS services, their data packet size is usually small, however, these services has the strict delay requirement. Hence, we assume that the DS data arriving each time must be served within the next SF which yields

$$(C14): T_{\mathsf{d}}R_{n,k}^{f^{\mathsf{d}},t_v^{\mathsf{d}}} \geq \lambda_{n,k,t_v}^{\mathsf{d}},\forall n,\forall k\in\mathcal{U}^{\mathsf{d}},\forall t_v.$$

Assuming there is one buffer for each service, the queue length corresponding to traffic flow k at $\mathsf{BS}_n/\mathsf{LSat}$ of MS and SS services is expressed as

$$q_{n,k}^{\mathsf{m},t_s^{\mathsf{m}}+1} = [q_{n,k}^{\mathsf{m},t_s^{\mathsf{m}}} + \lambda_{n,k,t_s^{\mathsf{m}}}^{\mathsf{m}} - T_{\mathsf{m}}R_{n,k}^{\mathsf{m},t_s^{\mathsf{m}}}]^+,\forall n,\forall k\in\mathcal{U}^{\mathsf{m}},$$

$$q_{0,k}^{\mathsf{x},t_s^{\mathsf{x}}+1} = [q_{0,k}^{\mathsf{x},t_s^{\mathsf{x}}} + \lambda_{0,k,t_s^{\mathsf{x}}}^{\mathsf{x}} - T_{\mathsf{x}}R_{0,k}^{\mathsf{x},t_s^{\mathsf{x}}}]^+,\forall k\in\mathcal{U}^{\mathsf{x}},\forall\mathsf{x}\in\mathcal{S}^{\mathsf{sn}},$$

where $[\cdot]^+ = \max\{0,\cdot\}$. Note that the data arrival of $\mathsf{x}\in\mathcal{S}^{\mathsf{sn}}$ will be served at the next TF. Hence, for $\mathsf{x}\in\mathcal{S}^{\mathsf{sn}}$, we set

$$\begin{cases}\lambda_{n,k,t_s^{\mathsf{x}}}^{\mathsf{x}} = \lambda_{n,k,t}^{\mathsf{x}},\ \lambda_{0,k,t_s^{\mathsf{x}}}^{\mathsf{x}} = \lambda_{0,k,t}^{\mathsf{x}} \text{ if } s=1,\\ \lambda_{n,k,t_s^{\mathsf{x}}}^{\mathsf{x}} = 0,\ \lambda_{0,k,t_s^{\mathsf{x}}}^{\mathsf{x}} = 0 \text{ in otherwise.}\end{cases} \quad (6)$$

To ensure stability, the queue lengths must satisfy

$$(C15): q_n^{\mathsf{m},t_s^{\mathsf{m}}} = \sum_{\forall k\in\mathcal{U}^{\mathsf{m}}} q_{n,k}^{\mathsf{m},t_s^{\mathsf{m}}} \le q_n^{\mathsf{m,max}}, \forall n, \forall t_s^{\mathsf{m}},$$
$$(C16): q_0^{\mathsf{x},t_s^{\mathsf{x}}} = \sum_{\forall k\in\mathcal{U}^{\mathsf{x}}} q_{0,k}^{\mathsf{x},t_s^{\mathsf{x}}} \le q_0^{\mathsf{x,max}}, \forall t_s^{\mathsf{x}}, \mathsf{x}\in\mathcal{S}^{\mathsf{sn}},$$

wherein $q_n^{\mathsf{m,max}}$ and $q_0^{\mathsf{x,max}}$ are the maximum queue-length at AP_n and the LSat, respectively. For convenience, let's denote $\boldsymbol{q}_c^{\mathsf{tn}} = \{q_n^{\mathsf{m},t_s^{\mathsf{m}}} | \forall n, \forall t_s^{\mathsf{m}} \in \mathcal{T}_c^{\mathsf{ts,m}}\}$, $\boldsymbol{q}_c^{\mathsf{sn}} = \{q_0^{\mathsf{x},t_s^{\mathsf{x}}} | \forall t_s^{\mathsf{x}} \in \mathcal{T}_c^{\mathsf{ts,x}}, \forall \mathsf{x} \in \mathcal{S}^{\mathsf{sn}}\}$, and $\boldsymbol{q}_c \triangleq \{\boldsymbol{q}_c^{\mathsf{tn}}, \boldsymbol{q}_c^{\mathsf{sn}}\}$.

Remark 1. *The arrival DS data is served within the next SF ensured by* $(C15)$. *Hence, the corresponding buffer is cleared after each SF, the queue length of DS ones is not considered.*

D. Problem Formulation

1) Centralized Problem: Leveraging the predicted information provided by the DT at the core-network in TC c, we aim to minimize the system congestion by optimizing the BW allocation, traffic split decision, AP-UE and LSat-UE associations, RB assignment, and power control under the latency requirement of DS services. Hence, the objective function is the sum queue length of MS and SS services at APs and LSats in each TC c which is defined as

$$f_c^{\mathsf{obj}}(\boldsymbol{q}_c) = \sum_{\forall n, \forall t_s^{\mathsf{m}}\in\mathcal{T}_c^{\mathsf{ts,m}}} q_n^{\mathsf{m},t_s^{\mathsf{m}}} + \sum_{\mathsf{x}\in\mathcal{S}^{\mathsf{sn}}, \forall t_s^{\mathsf{x}}\in\mathcal{T}_c^{\mathsf{ts,x}}} q_0^{\mathsf{x},t_s^{\mathsf{x}}}. \quad (7)$$

The optimization problem is mathematically formulated as

$$(\mathcal{P}_0)_c: \min_{\boldsymbol{\Omega}_c} f_c^{\mathsf{obj}}(\boldsymbol{q}_c) \quad \text{s.t. } (C1)-(C16),$$
$$(C0): b_{f^{\mathsf{x}},c}^{\mathsf{x}}, \alpha_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}}, \beta_{m,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}} \in \{0,1\}, \forall (m,n,k,f^{\mathsf{x}},t_s^{\mathsf{x}},\mathsf{x},c),$$

where $\boldsymbol{\Omega_c} \triangleq \{\boldsymbol{b}_c, \omega_c, \boldsymbol{p}_c, \boldsymbol{P}_c, \boldsymbol{\alpha}_c, \boldsymbol{\beta}_c, \boldsymbol{q}_c\}$. Problem $(\mathcal{P}_0)_c$ is very challenging to solve due to the coupling between the binary and continuous variables.

2) Calibration Problem: Since the prediction information of channel gain and arrival traffic may differ from that in the actual system, the solution for problem $(\mathcal{P}_0)$ should be adjusted appropriately. Specifically, based on actual channel gain at each TS, for the given $\boldsymbol{b}_c$, ω_c, $\boldsymbol{\alpha}_c, \boldsymbol{\beta}_c$, and $\boldsymbol{P}_c$, the AP power calibration problem can be formulated as

$$(\mathcal{P}_0^{\mathsf{cali}})_c: \min_{\boldsymbol{p}_c, \boldsymbol{\eta}_c, \boldsymbol{q}_c} f_c^{\mathsf{obj}}(\boldsymbol{q}_c) \quad \text{s.t. } (C10), (C11), (C14)-(C16).$$

3) Overall work flow: The workflow is summarized as
①Using update information, DT model predicts $\{\hat{\boldsymbol{h}}_c, \hat{\boldsymbol{g}}_c, \hat{\boldsymbol{\lambda}}_c\}$.
②Using $\{\hat{\boldsymbol{h}}_c, \hat{\boldsymbol{g}}_c, \hat{\boldsymbol{\lambda}}_c\}$, problem $(\mathcal{P}_0)_c$ is solved for TC c.
③Based on actual $\{\boldsymbol{h}_c, \boldsymbol{g}_c, \boldsymbol{\lambda}_c\}$, and the given solution in step 2, the power control at APs is calibrated by solving $(\mathcal{P}_0^{\mathsf{cali}})$.

III. Proposed Solutions

A. Compressed-Sensing-Based and Binary Relaxation

To solve problem $(\mathcal{P}_0)$ efficiently, the difficulty in solving due to binary variables should be addressed. Considering the system model and problem $(\mathcal{P}_0)$, one can see the relationship between the variable pairs $\{\boldsymbol{\alpha}_t, \boldsymbol{p}_t\}$ and $\{\boldsymbol{\beta}_t, \boldsymbol{P}_t\}$ as follows.

- If UE_k is served by AP_n via $\mathrm{RB}(f^{\mathsf{x}}, t_s^{\mathsf{x}})$, $\alpha_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = 1$ and $p_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}} > 0$, otherwise $\alpha_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = 0$ and $p_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = 0$.
- If UE_k is served by the LSat via $\mathrm{RB}(f^{\mathsf{x}}, t_s^{\mathsf{x}})$, $\beta_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = 1$ and $P_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}} > 0$, otherwise $\beta_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = 0$ and $P_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = 0$.

Based on this relationship, the $\boldsymbol{\alpha}_t$ and $\boldsymbol{\beta}_t$ can be respectively represented by $\boldsymbol{p}_t$ and $\boldsymbol{P}_t$ as [2], [16]

$$\alpha_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = \|p_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}}\|_0,\ \beta_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = \|P_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}}\|_0, \forall (n,m,k,f^{\mathsf{x}},t_s^{\mathsf{x}}). \quad (8)$$

Considering $(C4)$ and $(C7)$, $b_{f^{\mathsf{x}},c}^{\mathsf{x}} = 1$ if $\alpha_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = 1$ or $\beta_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}} = 1$. Hence, combine with (8), $\boldsymbol{b}$ is represented as

$$b_{f^{\mathsf{d}},c}^{\mathsf{d}} = \| \sum_{\forall (n,k), \forall t_s^{\mathsf{d}}\in\mathcal{T}_c^{\mathsf{ts,d}}} \alpha_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}} \|_0 = \|p_c^{\mathsf{d},f^{\mathsf{d}}}\|_0,\ \forall (f^{\mathsf{d}}, c), \quad (9a)$$
$$b_{f^{\mathsf{m}},c}^{\mathsf{m}} = \| \sum_{\forall (n,k), \forall t_s^{\mathsf{m}}\in\mathcal{T}_c^{\mathsf{ts,d}}} \alpha_{n,k}^{f^{\mathsf{m}},t_s^{\mathsf{m}}} + \sum_{\forall k, \forall t_s^{\mathsf{m}}\in\mathcal{T}_c^{\mathsf{ts,d}}} \beta_k^{f^{\mathsf{m}},t_s^{\mathsf{m}}} \|_0 = \|p_c^{\mathsf{m},f^{\mathsf{m}}} + P_c^{\mathsf{m},f^{\mathsf{m}}}\|_0,\ \forall (f^{\mathsf{m}}, c), \quad (9b)$$
$$b_{f^{\mathsf{s}},c}^{\mathsf{s}} = \| \sum_{\forall k, \forall t_s^{\mathsf{s}}\in\mathcal{T}_c^{\mathsf{ts,s}}} \beta_k^{f^{\mathsf{s}},t_s^{\mathsf{s}}} \|_0 = \|P_c^{\mathsf{s},f^{\mathsf{s}}}\|_0,\ \forall (f^{\mathsf{s}}, c). \quad (9c)$$

where $p_c^{\mathsf{x},f^{\mathsf{x}}} = \sum_{\forall (n,k) \forall t_s^{\mathsf{x}}\in\mathcal{T}_c^{\mathsf{ts,d}}} p_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}}$ and $P_c^{\mathsf{x},f^{\mathsf{x}}} = \sum_{\forall k \forall t_s^{\mathsf{x}}\in\mathcal{T}_c^{\mathsf{ts,d}}} P_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}}$. Thanks to (9), constraints $(C4)$ and $(C7)$ can be omitted.

Utilize relationships (8), the binary components in rate and SINR functions can be replaced by the corresponding ℓ_0-norm components. Moreover, the binary variables in the production components of association and transmit power variables can be omitted. Specifically, $R_{n,k}^{\mathsf{d},t_v^{\mathsf{d}}}(\boldsymbol{p}_t, \boldsymbol{\alpha}_t)$ is reformulated as

$$R_{n,k}^{\mathsf{d},t_v^{\mathsf{d}}}(\boldsymbol{p}_t) = w_{\mathsf{d}} \sum_{\forall (f^{\mathsf{d}},t_s^{\mathsf{d}})\in(\mathcal{F}^{\mathsf{d}}\times\mathcal{T}_{t_v}^{\mathsf{sf,d}})} \ln(1+\gamma_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}(\boldsymbol{p}_t)) - \chi_{\mathsf{d}} \sqrt{\sum_{\forall (f^{\mathsf{d}},t_s^{\mathsf{d}})\in(\mathcal{F}^{\mathsf{d}}\times\mathcal{T}_{t_v}^{\mathsf{sf,d}})} \|p_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}\|_0}. \quad (10)$$

Hence, arguments $\boldsymbol{\alpha}_t, \boldsymbol{\beta}_t$ in the rate/SINR functions is omitted.

Subsequently, to address the sparsity terms, the ℓ_0-norm component $\|x\|_0, \forall x \ge 0$ can be approximated as $\|x\|_0 \approx f_{\mathsf{ap}}(x)$ wherein $f_{\mathsf{ap}}(x) \triangleq 1 - e^{-x/\epsilon}$, $0 < \epsilon \ll 1$ is a concave function [12], [13]. Moreover, let $f_{\mathsf{ap}}^{(i)}(x)$ be an upper bound of $f_{\mathsf{ap}}(x)$ at feasible point $(x^{(i)})$, the ℓ_0-norm components in (8), (9) can be approximated at iteration i as

$$\|\iota\|_0 \approx f_{\mathsf{ap}}(\iota) \le f_{\mathsf{ap}}^{(i)}(\iota), \iota \in \{p_{n,k}^{f^{\mathsf{x}},t_s^{\mathsf{x}}}, P_k^{f^{\mathsf{x}},t_s^{\mathsf{x}}}, p_c^{f^{\mathsf{x}}}, P_c^{f^{\mathsf{x}}}\}, \quad (11)$$

where upper bound $f_{\mathsf{ap}}^{(i)}(x)$ can be obtained based on [13] as

$$f_{\mathsf{ap}}(x) \le f_{\mathsf{ap}}^{(i)}(x) \triangleq 1/\epsilon \exp(-x^{(i)}/\epsilon)(x - x^{(i)} - \epsilon) + 1. \quad (12)$$

Applying approximations in (8), (9) and (11), by replacing binary component of $\boldsymbol{b}_c$, $\boldsymbol{\alpha}_t$, and $\boldsymbol{\beta}_t$ by the corresponding approximated $f_{\mathsf{ap}}^{(i)}(\cdot)$ in constraints $(C1)-(C3), (C5), (C6), (C8)-(C9)$, we directly obtained convex constraints which are named as $\boldsymbol{(\tilde{C}1)-(\tilde{C}3), (\tilde{C}5), (\tilde{C}6), (\tilde{C}8)-(\tilde{C}9)}$, respectively, and $(C10)$ is approximated by non-convex constraint $(\bar{C}10)$ as

$$(\bar{C}10): \gamma_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}}(\boldsymbol{p}_t) \ge f_{\mathsf{ap}}^{(i)}(p_{n,k}^{f^{\mathsf{d}},t_s^{\mathsf{d}}})\gamma_0^{\mathsf{d}},\ \forall n, \forall k \in \mathcal{U}^{\mathsf{d}}, \forall (f^{\mathsf{d}}, t_s^{\mathsf{d}}).$$

Algorithm 1 PREDICTED INFORMATION ALGORITHM WITH RE-OPTIMIZATION (PI-AWRO)

Phase 1: Optimization for TC C with predicted $\hat{\boldsymbol{h}}_c$, $\hat{\boldsymbol{g}}_c$, $\hat{\lambda}_c$ from DT.
Set $i = 1$ and generate an initial point $(\boldsymbol{p}_c^{(0)}, \boldsymbol{P}_c^{(0)}, \boldsymbol{\eta}_c^{(0)})$.
repeat
  Solve problem $(\mathcal{P}_2)_c$ to obtain $(\boldsymbol{p}_c^\star, \boldsymbol{P}_c^\star, \boldsymbol{\eta}_c^\star)$.
  Update $(\boldsymbol{p}_c^{(i)}, \boldsymbol{P}_c^{(i)}, \boldsymbol{\eta}_c^{(i)}) = (\boldsymbol{p}_c^\star, \boldsymbol{P}_c^\star, \boldsymbol{\eta}_c^\star)$ and $i := i + 1$.
until Convergence
Recovery binary solutions $\boldsymbol{\alpha}_c$, $\boldsymbol{\beta}_c$, and $\boldsymbol{b}_c$ by (15) and (9).
Output 1: The solution for problem $\{\boldsymbol{b}_c^\star, \boldsymbol{\omega}_c^\star, \boldsymbol{p}_c^\star, \boldsymbol{P}_c^\star, \boldsymbol{\alpha}_c^\star, \boldsymbol{\beta}_c^\star, \boldsymbol{q}_c^\star\}$.
Phase 2: Re-optimize with actual $\boldsymbol{h}_t, \boldsymbol{g}_t, \boldsymbol{\lambda}_t$ and initial point by **Output 1**.
for Each TF t in TC c **do**
  repeat
    Solve problem $(\mathcal{P}_1^{\mathsf{cali}})_c$ to obtain $(\boldsymbol{p}_t^\star, \boldsymbol{\eta}_t^\star)$.
    Update $(\boldsymbol{p}_t^{(i)}, \boldsymbol{\eta}_t^{(i)}) = (\boldsymbol{p}_t^\star, \boldsymbol{\eta}_t^\star)$ and $i := i + 1$.
  until Convergence
end for
Output 2: The adjusted AP power control $\boldsymbol{p}_c^\star$.

B. Transform Traffic Steering and Queue Constraints

To address non-convex constraints $(C14) - (C16)$, we introduce an intermediate traffic split variable $\bar{\boldsymbol{\omega}} = \{\bar{\omega}^{\mathsf{x}}_{n,k,c} | \forall (n,k,c,\mathsf{x})\}$ and use it instead of $\omega^{\mathsf{cn}}_{k,c}$ and $\omega^{\mathsf{x}}_{n,k,c}$ with the relationship $\bar{\omega}^{\mathsf{x}}_{n,k,c} = \omega^{\mathsf{d}}_{n,k,c}$ if $\mathsf{x} \equiv \mathsf{d}$, $\bar{\omega}^{\mathsf{x}}_{n,k,c} = \omega^{\mathsf{cn}}_{k,c}\omega^{\mathsf{m}}_{n,k,c}$ if $\mathsf{x} \equiv \mathsf{m}$. Hence, constraint $(C13)$ is rewritten as

$$(\tilde{C}13): \quad \textstyle\sum_{\forall n \in \mathcal{N}} \bar{\omega}^{\mathsf{d}}_{n,k,c} = 1, \forall k \in \mathcal{U}^{\mathsf{d}}, \forall c,$$

Furthermore, the traffic arrival formula (5) is rewritten as

$$\lambda^{\mathsf{d}}_{n,k,t_v} = \bar{\omega}^{\mathsf{d}}_{n,k,c}\lambda^{\mathsf{d}}_{k,t_v}, \quad \lambda^{\mathsf{m}}_{n,k,t} = \bar{\omega}^{\mathsf{m}}_{n,k,c}\lambda^{\mathsf{m}}_{k,t}, \tag{13a}$$
$$\lambda^{\mathsf{m}}_{0,k,t} = (1 - \textstyle\sum_{\forall n} \bar{\omega}^{\mathsf{m}}_{n,k,c})\lambda^{\mathsf{m}}_{k,t}, \quad \lambda^{\mathsf{s}}_{0,k,t} = \lambda^{\mathsf{s}}_{k,t}. \tag{13b}$$

Additionally, we introduce slack variables $\bar{\boldsymbol{q}}_c = \{\bar{q}^{\mathsf{x},t_s^{\mathsf{x}}}_{n,k}, \bar{q}^{\mathsf{x},t_s^{\mathsf{x}}}_{0,k} | \forall (n,k), \forall t_s^{\mathsf{x}} \in \mathcal{T}_c^{\mathsf{ts},\mathsf{x}}, \forall \mathsf{x} \in \mathcal{S}\}$ as the upper bound of the queue length and $\boldsymbol{r}_c = \{r^{\mathsf{x},t_s^{\mathsf{x}}}_{n,k}, r^{\mathsf{x},f^{\mathsf{x}},t_s^{\mathsf{x}}}_{n,k}, r^{\mathsf{x},t_s^{\mathsf{x}}}_{0,k}, r^{\mathsf{x},f^{\mathsf{x}},t_s^{\mathsf{x}}}_{0,k} | \forall (n,k), \forall t_s^{\mathsf{x}} \in \mathcal{T}_c^{\mathsf{ts},\mathsf{x}}, \forall \mathsf{x} \in \mathcal{S}\}$ as the rate's lower bound, and relax $(C15) - (C16)$ as

$$(\tilde{C}14): \quad T_{\mathsf{d}} r^{f^{\mathsf{d}},t_v^{\mathsf{d}}}_{n,k} \geq \lambda^{\mathsf{d}}_{n,k,t_v}, \forall n, \forall k \in \mathcal{U}^{\mathsf{d}}, \forall t_v,$$
$$(\tilde{C}15a): \bar{q}^{\mathsf{m},t_s^{\mathsf{m}}}_{n,k} + \lambda^{\mathsf{m}}_{n,k,t_s^{\mathsf{m}}} - T_{\mathsf{m}} r^{\mathsf{m},t_s^{\mathsf{m}}}_{n,k} \leq \bar{q}^{\mathsf{m},t_s^{\mathsf{m}}+1}_{n,k}, \forall n, \forall t_s^{\mathsf{m}},$$
$$(\tilde{C}15b): 0 \leq \bar{q}^{\mathsf{m},t_s^{\mathsf{m}}}_{n,k}, \textstyle\sum_{\forall k \in \mathcal{U}^{\mathsf{m}}} \bar{q}^{\mathsf{m},t_s^{\mathsf{m}}}_{n,k} \leq q^{\mathsf{m},\max}_{n}, \forall n, \forall t_s^{\mathsf{m}},$$
$$(\tilde{C}16a): \bar{q}^{\mathsf{x},t_s^{\mathsf{x}}}_{0,k} + \lambda^{\mathsf{x}}_{0,k,t_s^{\mathsf{x}}} - T_{\mathsf{x}} r^{\mathsf{x},t_s^{\mathsf{x}}}_{0,k} \leq \bar{q}^{\mathsf{x},t_s^{\mathsf{x}}+1}_{0,k}, \forall t_s^{\mathsf{x}}, \forall \mathsf{x} \in \mathcal{S}^{\mathsf{sn}},$$
$$(\tilde{C}16b): 0 \leq \bar{q}^{\mathsf{x},t_s^{\mathsf{x}}}_{0,k}, \textstyle\sum_{\forall k \in \mathcal{U}^{\mathsf{x}}} \bar{q}^{\mathsf{x},t_s^{\mathsf{x}}}_{0,k} \leq q^{\mathsf{x},\max}_{0}, \forall m, \forall t_s^{\mathsf{x}}, \forall \mathsf{x} \in \mathcal{S}^{\mathsf{sn}},$$

where $r^{\mathsf{m},t_s^{\mathsf{m}}}_{n,k} = \sum_{\forall f^{\mathsf{s}}} r^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k}$, $r^{\mathsf{x},t_s^{\mathsf{x}}}_{0,k} = \sum_{\forall f^{\mathsf{s}}} r^{\mathsf{x},f^{\mathsf{x}},t_s^{\mathsf{x}}}_{0,k}, \forall \mathsf{x} \in \mathcal{S}^{\mathsf{sn}}$ while $r^{f^{\mathsf{x}},t_s^{\mathsf{x}}}_{n,k}$ and $r^{f^{\mathsf{x}},t_s^{\mathsf{x}}}_{0,k}$ satisfy constraints

$$(C17.1): R^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k}(\boldsymbol{p}_t) \geq r^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k}, \ \forall n, \forall k \in \mathcal{U}^{\mathsf{m}}, \forall t_s^{\mathsf{m}} \in \mathcal{T}_c^{\mathsf{ts},\mathsf{m}},$$
$$(C17.2): R^{\mathsf{d},t_v^{\mathsf{d}}}_{n,k}(\boldsymbol{p}_t) \geq r^{\mathsf{d},t_v^{\mathsf{d}}}_{n,k}, \ \forall n, \forall k \in \mathcal{U}^{\mathsf{d}}, \forall t_v^{\mathsf{d}},$$
$$(C18): R^{\mathsf{x},f^{\mathsf{x}},t_s^{\mathsf{x}}}_{0,k}(\boldsymbol{P}_t) \geq r^{\mathsf{x},f^{\mathsf{x}},t_s^{\mathsf{x}}}_{0,k}, \ \forall k \in \mathcal{U}^{\mathsf{x}}, \forall t_s^{\mathsf{x}} \in \mathcal{T}_c^{\mathsf{ts},\mathsf{x}}, \forall \mathsf{x} \in \mathcal{S}^{\mathsf{sn}},$$

Therefore, problem $(\mathcal{P}_0)$ can be rewritten as

$$(\mathcal{P}_1)_c: \min_{\bar{\boldsymbol{\omega}}_c, \boldsymbol{p}_c, \boldsymbol{P}_c, \bar{\boldsymbol{q}}_c, \boldsymbol{r}_c} \quad f_c^{\mathsf{obj}}(\bar{\boldsymbol{q}}_c)$$
$$\text{s.t.} \quad (\tilde{C}1) - (\tilde{C}3), (\tilde{C}5), (\tilde{C}6), (\tilde{C}8), (\tilde{C}9), (\bar{C}10),$$
$$(C11), (C12), (\tilde{C}14) - (\tilde{C}16), (C17), (C18).$$

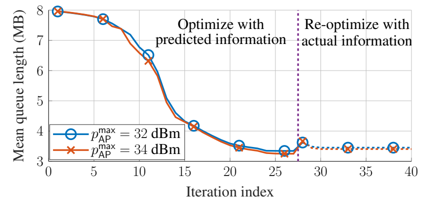

Fig. 2: Convergence rate of the proposed algorithm.

Problem $(\mathcal{P}_1)$ is still non-convex due to $(\bar{C}10)$,$(C17)$,$(C18)$, which are convexified by the following Propositions.

Proposition 1. *Constraints $(C17.1)$, $(C18)$ are convexified as*

$$(\tilde{C}17a): f^{\mathsf{rate},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k}(\boldsymbol{p}_t, \boldsymbol{P}_t, \boldsymbol{\eta}_t^{\mathsf{a}}) \geq r^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k},$$
$$(\tilde{C}17b): \Psi^{f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k}(\boldsymbol{p}_t) + \Theta^{\mathsf{a},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{k}(\boldsymbol{P}_t) + \sigma^2_{\mathsf{m},k} \leq f^{(i)}_{\exp}(\eta^{\mathsf{a},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k}),$$
$$(\tilde{C}18a): f^{\mathsf{rate},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{0,k}(\boldsymbol{p}_t, \boldsymbol{P}_t, \boldsymbol{\eta}_t^{\mathsf{s}}) \geq r^{\mathsf{m},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{0,k},$$
$$(\tilde{C}18b): \Theta^{\mathsf{s},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{k}(\boldsymbol{p}_t) + \sigma^2_{\mathsf{m},k} \leq f^{(i)}_{\exp}(\eta^{\mathsf{s},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{0,k}),$$
$$(\tilde{C}18c): R^{\mathsf{s},f^{\mathsf{s}},t_s^{\mathsf{s}}}_{0,k}(\boldsymbol{P}_t) \geq r^{\mathsf{s},f^{\mathsf{s}},t_s^{\mathsf{s}}}_{0,k},$$

with $f^{(i)}_{\exp}(u) \triangleq \exp(u^{(i)})(u - u^{(i)} + 1)$, $f^{\mathsf{rate},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k}(\boldsymbol{p}_t, \boldsymbol{P}_t, \boldsymbol{\eta}_t^{\mathsf{a}}) = w_{\mathsf{m}}(\ln(p^{f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k} h^{f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k} + \Psi^{f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k}(\boldsymbol{p}_t) + \Theta^{\mathsf{a},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{k}(\boldsymbol{P}_t) + \sigma^2_{\mathsf{m},k}) - \eta^{\mathsf{a},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{n,k})$*, and* $f^{\mathsf{rate},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{0,k}(\boldsymbol{p}_t, \boldsymbol{P}_t, \boldsymbol{\eta}_t^{\mathsf{s}}) = w_{\mathsf{m}}(\ln(P^{f^{\mathsf{m}},t_s^{\mathsf{m}}}_{k} g^{f^{\mathsf{m}},t_s^{\mathsf{m}}}_{k} + \Theta^{\mathsf{s},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{k}(\boldsymbol{p}_t) + \sigma^2_{\mathsf{m},k}) - \eta^{\mathsf{s},f^{\mathsf{m}},t_s^{\mathsf{m}}}_{0,k})$.

Proof: Consider $f_{\mathsf{r}}(x,y) = \ln(1 + \frac{x}{y+a}), x, y \geq 0, a > 0$, constraint $f_{\mathsf{r}}(x,y) \geq z$, $z \geq 0$ is approximated as [12], [13]

$$\ln(x + y + a) \geq z + u, \quad y + a \leq f^{(i)}_{\exp}(u). \tag{14}$$

Apply (14) to log component in rate functions with corresponding values x, y, a, and u, $(C17.1)$ and $(C18)$ are convexified by $(\tilde{C}17)$ and $(\tilde{C}18)$, respectively. ■

Proposition 2. *Constraint $(\bar{C}10)$ can be approximated as*

$$(\tilde{C}10a): f^{\mathsf{rate},f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}(\boldsymbol{p}_t, \boldsymbol{\eta}_t^{\mathsf{a}}) \geq f^{(i)}_{\mathsf{ap}}(p^{f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}) \ln(1 + \gamma_0^{\mathsf{d}}),$$
$$(\tilde{C}10b): \Psi^{f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}(\boldsymbol{p}_t) + \sigma^2_{\mathsf{d},k} \leq f^{(i)}_{\exp}(\eta^{\mathsf{a},f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}),$$

$$f^{\mathsf{rate},f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}(\boldsymbol{p}_t, \boldsymbol{\eta}_t^{\mathsf{a}}) = w_{\mathsf{d}}(\ln(p^{f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k} h^{f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k} + \Psi^{f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}(\boldsymbol{p}_t) + \sigma^2_{\mathsf{d},k}) - \eta^{\mathsf{a},f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k})$$

Proof: Constraint $(\bar{C}10)$ is transformed equivalently as

$$\ln(1 + \gamma^{f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}(\boldsymbol{p}_t)) \geq f^{(i)}_{\mathsf{ap}}(p^{f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}) \ln(1 + \gamma_0^{\mathsf{d}}), \ \forall n, \forall k, \forall (f^{\mathsf{d}}, t_s^{\mathsf{d}}).$$

This constraint is approximated similarly to Proposition 1. ■

Proposition 3. *Rate constraint $(C17.2)$ is approximated as*

$$(\tilde{C}17c): \sum_{\forall f^{\mathsf{d}} \in \mathcal{F}^{\mathsf{d}}} \sum_{\forall t_s^{\mathsf{d}} \in \mathcal{T}^{\mathsf{sf},\mathsf{d}}_{t_v}} f^{\mathsf{rate},f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}(\boldsymbol{p}_t, \boldsymbol{\eta}_t^{\mathsf{a}}) - \chi_{\mathsf{d}} f^{(i)}_{\mathsf{sqrt}}(\zeta^{t_v^{\mathsf{d}}}_{n,k}) \geq r^{\mathsf{d},t_v^{\mathsf{d}}}_{n,k},$$
$$(\tilde{C}17d): \zeta^{t_v^{\mathsf{d}}}_{n,k} \geq \textstyle\sum_{\forall f^{\mathsf{d}} \in \mathcal{F}^{\mathsf{d}}} \sum_{\forall t_s^{\mathsf{d}} \in \mathcal{T}^{\mathsf{sf},\mathsf{d}}_{t_v}} f^{(i)}_{\mathsf{ap}}(p^{f^{\mathsf{d}},t_s^{\mathsf{d}}}_{n,k}),$$

wherein $f^{(i)}_{\mathsf{sqrt}}(x) = 0.5x/\sqrt{x^{(i)}} + 0.5\sqrt{x^{(i)}}$.

Proof: The log component in $R^{\mathsf{d},t_v^{\mathsf{d}}}_{n,k}(\boldsymbol{p})$ is approximated as in Proposition 1. Applying (11) to ℓ_0-norm terms, we obtained the upper bound of the summation in the second term of

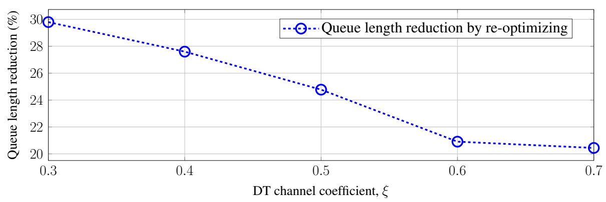

Fig. 3: Mean queue length reduction vs. DT channel coefficient ξ.

$R_{n,k}^{\mathsf{d},t_v^{\mathsf{d}}}(\boldsymbol{p})$ as $(\tilde{C}17d)$. Using SCA technique to obtain upper bound $f_{\mathsf{sqrt}}^{(i)}(\zeta_{n,k}^{t_v^{\mathsf{d}}}) \geq f_{\mathsf{sqrt}}(\zeta_{n,k}^{t_v^{\mathsf{d}}})$, we complete the proof. ■

Thanks to proposition 1, 2 and 3, problem $(\mathcal{P}_1)$ is transformed into an iterative convex problem $(\mathcal{P}_2)$ as

$$(\mathcal{P}_2)_c : \min_{\boldsymbol{\omega}_c, \boldsymbol{p}_c, \boldsymbol{P}_c, \bar{\boldsymbol{q}}_c, \boldsymbol{\eta}_c, \boldsymbol{\zeta}_c} f_c^{\mathsf{obj}}(\bar{\boldsymbol{q}}_c)$$

$$\text{s.t.}(\tilde{C}1)-(\tilde{C}3), (\tilde{C}5), (\tilde{C}6), (\tilde{C}8)-(\tilde{C}10), (C11), (C12), (\tilde{C}13)-(\tilde{C}18).$$

After solving problem $(\mathcal{P}_2)_c$, $\boldsymbol{\alpha}_c$ and $\boldsymbol{\beta}_c$ are recovered as

$$\alpha_{n,k}^{f^{\mathsf{x}},t_x^{\mathsf{x}}} = 1 \text{ if } p_{n,k}^{f^{\mathsf{x}},t_x^{\mathsf{x}}} \geq \epsilon \text{ and } \alpha_{n,k}^{f^{\mathsf{x}},t_x^{\mathsf{x}}} = 0 \text{ in otherwise,} \quad (15a)$$

$$\beta_{k}^{f^{\mathsf{x}},t_x^{\mathsf{x}}} = 1 \text{ if } P_{k}^{f^{\mathsf{x}},t_x^{\mathsf{x}}} \geq \epsilon \text{ and } \beta_{k}^{f^{\mathsf{x}},t_x^{\mathsf{x}}} = 0 \text{ in otherwise.} \quad (15b)$$

The BW allocation variable $\boldsymbol{b}_c$ is recovered by (9). Using approximated convex constraints above, $(\mathcal{P}_0^{\mathsf{cali}})_c$ is transformed into the iterative convex problem $(\mathcal{P}_1^{\mathsf{cali}})_c$ as

$$(\mathcal{P}_1^{\mathsf{cali}})_c : \min_{\boldsymbol{p}_c, \boldsymbol{\eta}_c, \bar{\boldsymbol{q}}_c} f_c^{\mathsf{obj}}(\bar{\boldsymbol{q}}_c) \quad \text{s.t. } (\tilde{C}10), (C11), (\tilde{C}14)-(\tilde{C}16).$$

The solution is summarized in Alg. 1, so-called PIAwRO.

IV. Numerical Results

We set the operation frequency $f_c = 3.4$ GHz, system BW $B = 15$ MHz, power budget at AP and LSat $p_{\mathsf{ap}}^{\mathsf{max}} = 34$ dBm, $p_{\mathsf{sat}}^{\mathsf{max}} = 36$ dBm, and number of DS, MS, SS UEs and APs $(K_{\mathsf{d}}, K_{\mathsf{m}}, K_{\mathsf{s}}, N) = (4, 5, 3, 6)$. The LEO altitude is 500 km, and LSat and AP antenna parameters are set according to [17], [18]. We consider $N_{\mathsf{cy}} = 20$ TCs where each consists of $N^{\mathsf{tf}} = 5$ TFs. For comparison purpose, we consider the following schemes: 1) FIA (Full information algorithm): use full actual information for optimization, 2) PIAwRO: proposed algorithm, 3) PIA: optimization with only predicted information (steps 1-8 of Alg. 1), and 4) Greedy algorithm: fixed BW allocation, $(\boldsymbol{\alpha}_c, \boldsymbol{\beta}_c)$ selected based on channel gain, water-filling-based power control, and traffic steering set proportional to UE rate.

Fig. 2 depicts the convergence rate in two phases of Alg. 1 in different $p_{\mathsf{AP}}^{\mathsf{max}}$ values. One can see that Alg. 1 converges after only about 30 iterations. Especially, with the aid of DT, phase 1 can provide a sufficiently good initial point so that phase 2 only requires about 3 iterations for convergence.

Fig. 3 shows the gain of re-optimizing in terms of queue length reduction versus the DT channel coefficient ξ. One notes that a larger ξ indicates a more accurate replication of DT. Hence, the gain of re-optimizing decreases as ξ increases due to the DT is closer to the actual environment.

Fig. 4 shows the mean queue length outcome of the four considered schemes versus the AP power budget. Compared to the greedy algorithm, the three optimization-based algorithms are superior in minimizing the queue length. Especially, the gap between PIAwPO and FIA is only about $0.5 - 0.9$ MB. This figure further shows the gain of re-optimizing, i.e, re-optimizing $\boldsymbol{p}_t$ can reduce mean queue length by about 1 MB.

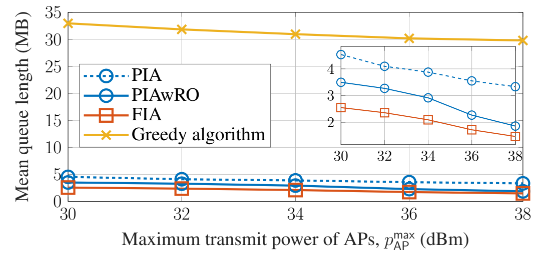

Fig. 4: Mean queue length versus AP power budget $p_{\mathsf{AP}}^{\mathsf{max}}$.

V. Conclusion

This work studied a DT-aided framework for resource management ISTNs, where TNs and SNs coexist over the same RFB. By leveraging a time-varying DT model with the 3D map, we jointly optimized BW allocation, traffic steering, UE/RB assignment, and power control, under delay service constraints. Subsequently, we proposed an SCA-based two-phase algorithm to solve the optimization problem. Numerical evaluations validated the superiority of our approach in minimizing queue lengths compared to benchmarks, highlighting its potential to support dynamic and spectrum-sharing ISTNs.

References

[1] FCC, “Single network future: Supplemental coverage from space,” 2023.

[2] H. Nguyen-Kha, V. N. Ha, E. Lagunas, S. Chatzinotas, and J. Grotz, “Joint two-tier user association and resource management for integrated satellite-terrestrial networks,” *IEEE Trans. Wireless Commun.*, 2024.

[3] ——, “LEO-to-user assignment and resource allocation for uplink transmit power minimization,” in *Proc. WSA & SCC 2023*, 2023.

[4] ——, “An experimental study of C-band channel model in integrated LEO satellite and terrestrial systems,” in *Proc. MeditCom 2024*, 2024.

[5] N. Okati *et al.*, “Co-existence of terrestrial and non-terrestrial networks in S-band,” 2024, arXiv:2401.08453.

[6] D. Kim, J. Park, J. Choi, and N. Lee, “Spectrum sharing between low earth orbit satellite and terrestrial networks: A stochastic geometry perspective analysis,” 2024, arXiv:2408.12145.

[7] H.-W. Lee, C.-C. Chen, S. Liao, A. Medles, D. Lin, I.-K. Fu, and H.-Y. Wei, “Interference mitigation for reverse spectrum sharing in B5G/6G satellite-terrestrial networks,” *IEEE Trans. Veh. Technol.*, pp. 1–16, 2023.

[8] Z. Li, S. Han, M. Peng, C. Li, and W. Meng, “Dynamic multiple access based on RSMA and spectrum sharing for integrated satellite-terrestrial networks,” *IEEE Trans. Wireless Commun.*, 2024.

[9] H. Martikainen, M. Majamaa, and J. Puttonen, “Coordinated dynamic spectrum sharing between terrestrial and non-terrestrial networks in 5G and beyond,” in *IEEE Int. Symposium WoWMoM*, 2023, pp. 419–424.

[10] J. Zhu, Y. Sun, and M. Peng, “Beam management in low earth orbit satellite communication with handover frequency control and satellite-terrestrial spectrum sharing,” *IEEE Trans. Commun.*, pp. 1–1, 2024.

[11] A. B. Kihero, M. S. J. Solaija, and H. Arslan, “Inter-numerology interference for beyond 5g,” *IEEE Access*, vol. 7, 2019.

[12] H. Nguyen-Kha, V. N. Ha, E. Lagunas, S. Chatzinotas, and J. Grotz, “Seamless 5G automotive connectivity with integrated satellite terrestrial networks in c-band,” in *IEEE VTC2024-Fall*, 2024.

[13] ——, “Enhanced throughput and seamless handover solutions for urban 5G-automotive supported C-band integrated satellite-terrestrial networks,” *IEEE Trans. Commun.*, 2025.

[14] Y. Polyanskiy, H. V. Poor, and S. Verdu, “Channel coding rate in the finite blocklength regime,” *IEEE Trans. Informat. Theory*, vol. 56, 2010.

[15] S. Schiessl *et al.*, “Delay analysis for wireless fading channels with finite blocklength channel coding,” in *ACM MSWiM*, Nov. 2015.

[16] H. Nguyen-Kha, V. N. Ha, E. Lagunas, S. Chatzinotas, and J. Grotz, “Two-tier user association and resource allocation design for integrated satellite-terrestrial networks,” in *Proc. IEEE ICC Workshop*, 2023.

[17] 3GPP, “Study on New Radio (NR) to support non-terrestrial networks,” Tech. Rep. 38.811, Sept. 2020, version 15.4.0.

[18] 3GPP, “Solutions for NR to support non-terrestrial networks (NTN),” Technical Specification (TS) 38.863, Dec. 2023, 18.0.0.