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Special Topic: User-Centric Intelligent Networking

Freesat: enabling user-centric multi-satellite cooperative networks via AI-RAN

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Low Earth orbit (LEO) mega-constellations have emerged as a promising solution for global Internet coverage due to their low latency and wide-area connectivity [1]. Unlike traditional terrestrial networks that rely on fixed ground-based infrastructure, LEO satellites act as primary access nodes for user terminals (UTs) while moving at extremely high velocities in space. As a result, the communication link between a satellite and a UT typically lasts only a few minutes in most regions, after which a handover to another satellite becomes unavoidable [2]. The high frequency of handovers introduces substantial signaling overhead and control complexity, causing short but non-negligible service interruptions. Meanwhile, channel state information (CSI) in non-terrestrial networks (NTNs) is highly dynamic due to satellite mobility, high-frequency operation, atmospheric attenuation, and blockages [3]. These factors result in severe CSI fluctuations and unstable link quality.

Consequently, users may experience degraded quality of service (QoS), including increased latency, transient transmission disruptions, and reduced session reliability. Considerable efforts have been made to mitigate the impact of frequent handovers and improve QoS in NTNs [2]. However, most existing solutions assume that CSI is predetermined and remains relatively stable as satellites move, which is unrealistic in practice and often leads to significant performance gaps. While learning-based approaches have been proposed, they typically restrict each user terminal to a single-satellite association, limiting user-centric flexibility and preventing the realization of seamless, user-centric connectivity essential for next-generation NTN systems [4]. To this end, Freesat is proposed to enable user-centric connectivity in NTNs under dynamic channel conditions. Motivated by the powerful capabilities of artificial intelligence-driven radio access networks (AI-RAN) [5], Freesat adopts AI-RAN to allow multiple satellites to simultaneously serve a single UT, thereby enhancing QoS and alleviating bandwidth and handover bottlenecks. This multi-satellite cooperation is realized through multi-connectivity with traffic splitting, where each UT can simultaneously connect to multiple satellites

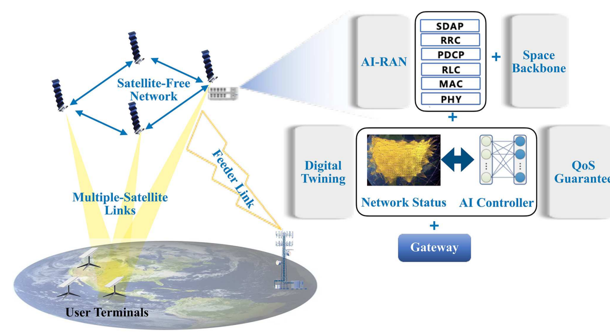

Figure 1 (Color online) Architecture of proposed SFN.

under capacity and QoS constraints, rather than through fully coordinated transmission or coherent processing.

Figure 1 shows the proposed AI-RAN-driven satellite-free networks (SFNs). Here, the term "satellite-free" does not imply the absence of satellites, but rather denotes the absence of exclusive cell-like associations. A SFN composed of M satellites, indexed by $\mathcal{M} = \{1, \ldots, M\}$, serving K mobile UTs, indexed by $\mathcal{K} = \{1, \ldots, K\}$, is considered. The QoS maximization problem in the SFN is formulated as

$$\mathbf{P0}: \quad \max_{\mathcal{X}} \ \lambda \sum_{k\in\mathcal{K}} \sum_{m\in\mathcal{M}} \sum_{t=0}^{T} x_{k,m}(t)\hat{R}_{k,m}(t)\Delta t + (\lambda - 1) \sum_{k\in\mathcal{K}} \sum_{m\in\mathcal{M}} \sum_{t=1}^{T} \frac{|x_{k,m}(t) - x_{k,m}(t-1)|}{2} \tag{1a}$$

$$\text{s.t.} \quad \sum_{m\in\mathcal{M}} x_{k,m}(t) \leqslant m^{\text{th}}, \quad \forall k \in \mathcal{K},\ \forall t \in [0, T], \tag{1b}$$

$$\hat{R}_{k,m}(t) \geqslant x_{k,m}(t) R_k^{\text{th}}(t), \quad \forall k, m, t, \tag{1c}$$

$$\sum_{k\in\mathcal{K}} \hat{R}_{k,m}(t) x_{k,m}(t) \leqslant C_m, \quad \forall m \in \mathcal{M},\ \forall t, \tag{1d}$$

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where $\mathcal{X} = \{x_{k,m}(t)\}$ denotes the satellite assignment decisions, and $x_{k,m}(t) \in \{0,1\}$ indicates whether UT-k is served by satellite-m in time frame t. $\hat{R}_{k,m}(t)$ indicates the ergodic user rate from user k to satellite m. The first term of (1a) captures the total transmission capacity, i.e., the accumulated rate across all UT-satellite pairs during T. The second term penalizes frequent handovers, where a handover is detected whenever $|x_{k,m}(t) - x_{k,m}(t-1)| = 1$. Notably, when user k switches its serving satellite from n to m, $n, m \in \mathcal{M}$, it holds that $|x_{k,m}(t) - x_{k,m}(t-1)| = 1$ and $|x_{k,n}(t) - x_{k,n}(t-1)| = 1$. As a result, the summation $\sum_{k\in\mathcal{K}}\sum_{m\in\mathcal{M}}\sum_{t=1}^{T}|x_{k,m}(t) - x_{k,m}(t-1)|$ counts each handover event twice. Therefore, the summation is divided by 2 to obtain the exact number of handover events. The weighting factor $\lambda \in [0,1]$ balances these two QoS aspects. A larger λ prioritizes throughput, while a smaller λ emphasizes stability by reducing handovers. The constraint (1b) ensures that each UT can be served by at most m^{th} satellites simultaneously. This reflects practical limitations on receiver processing capabilities and antenna resources. The constraint (1c) guarantees that whenever a UT is assigned to a satellite, the achieved ergodic rate must meet the minimum QoS requirement $R_k^{\text{th}}(t)$. This ensures that user-centric connectivity across different applications. The constraint (1d) enforces the finite processing and communication capacity of each satellite. Specifically, the aggregate service rates delivered by satellite-m cannot exceed its maximum capacity C_m, which may be limited by on-board computing power, feeder link bandwidth, or payload resources.

Next, an MPC-driven DT framework is employed to implement intelligent decision-making algorithms that generate a short-term control policy over the prediction horizon $[t_0+1, t_0+\tau]$. **P0** is reformulated as

$$\mathbf{P1}: \max_{\mathcal{X}_{t_0+1}^{t_0+\tau}} \quad \Phi \tag{2a}$$

$$\text{s.t.} \quad \sum_{m\in\mathcal{M}} x_{k,m}(t) \leqslant m^{\text{th}}, \quad \forall t, k, \tag{2b}$$

$$\hat{R}_{k,m}(t) \geqslant x_{k,m}(t) R_k^{\text{th}}(t), \quad \forall t, k, m, \tag{2c}$$

$$\sum_{k\in\mathcal{K}} \hat{R}_{k,m}(t) x_{k,m}(t) \leqslant C_m, \quad \forall t, m, \tag{2d}$$

$$x_{k,m}^{*}(t_0) = x_{k,m}(t_0), \quad \forall k, m. \tag{2e}$$

Here, Φ represents the objective that jointly captures transmission efficiency and handover cost over the time horizon $t \in [t_0+1, t_0+\tau]$, which is given by $\Phi = \lambda\sum_{k\in\mathcal{K}}\sum_{m\in\mathcal{M}}\sum_{t=t_0+1}^{t_0+\tau} x_{k,m}(t)\hat{R}_{k,m}(t)\Delta t + (\lambda - 1)\sum_{k\in\mathcal{K}}\sum_{m\in\mathcal{M}}\sum_{t=t_0+1}^{t_0+\tau}\frac{|x_{k,m}(t)-x_{k,m}(t-1)|}{2}$, where the first term quantifies the accumulated transmission efficiency and the second term accounts for the associated handover cost. By optimizing **P1**, Freesat determines a set of feasible control decisions $\mathcal{X}_{t_0+1}^{t_0+\tau}$ that adaptively respond to the predicted system state within the upcoming horizon.

Given that **P1** is a non-convex problem, direct optimization may lead to infeasibility. To address this issue, Freesat employs a safe learning framework that translates the objective into a trainable loss function

$$\begin{aligned}\mathcal{L} = &-\Phi + \mu_1 \sum_{k\in\mathcal{K}}\sum_{m\in\mathcal{M}}\sum_{t=t_0+1}^{t_0+\tau}\left[x_{k,m}(t)R_k^{\text{th}}(t) - \hat{R}_{k,m}(t)\right]^{+} \\ &+ \mu_2 \sum_{m\in\mathcal{M}}\sum_{t=t_0+1}^{t_0+\tau}\left[\sum_{k\in\mathcal{K}}\hat{R}_{k,m}(t)x_{k,m}(t) - C_m\right]^{+},\end{aligned} \tag{3}$$

where μ_1 and μ_2 are penalty coefficients that penalize constraint violations and guide the model toward QoS-compliant solutions. This formulation allows the AI-RAN to iteratively refine its decision-making model through gradient-based optimization. Moreover, before deployment, the resulting control policy is validated within the DT environment. If the policy satisfies all QoS constraints, it is executed in the physical network; otherwise, the DT adjusts the decision by exploring nearby feasible regions. The workflow of the DT framework is illustrated in Algorithm 1.

Algorithm 1 Digital twin workflow for online service provisioning.

Require: Constructed network state $\mathbf{\Psi}_{t_0-T_0}^{t_0-1}$;
Ensure: Control decisions;
while System operation = **True do**
  Collect the current network status;
  Update $\mathbf{\Psi}_{t_0-T_0+1}^{t_0}$ with the newly observed data;
  Predict network dynamics over the horizon $[t_0+1, t_0+\tau]$;
  Solve **P1** to generate a control policy $\mathcal{X}_{t_0+1}^{t_0+\tau}$;
  Validate the candidate policy within the DT;
  if All QoS constraints are satisfied **then**
    Forward the control decision $\boldsymbol{X}_{t_0+1}$ to the physical network;
  else
    Refine the decision through safe learning and output a feasible policy $\boldsymbol{X}_{t_0+1}$;
  end if
  $t_0 \leftarrow t_0 + 1$;
end while

In a nutshell, Freesat provides a user-centric SFN framework that enables multiple satellites to cooperatively serve a single UT, overcoming frequent handovers and ensuring QoS. The framework leverages an AI-RAN architecture with a DT controller to dynamically coordinate multi-satellite associations, predict short-term network states, and validate control decisions under highly dynamic SFN conditions. Freesat lays the foundation for next-generation 6G direct-to-cell communication systems, enabling seamless, resilient, and truly user-centric connectivity.

The detailed operation of the proposed AI-RAN-enabled framework is presented in Appendix A. The channel model and the definition of $\hat{R}$ are provided in Appendix B, while detailed analyses and discussions are included in Appendix C. The related work is discussed in Appendix D.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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