Layered Content Delivery over Satellite Integrated Cognitive Radio Networks

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***Abstract*—The inefficient and inflexible utilization of radio spectrum has led to the Cognitive Radio (CR) concept where licensed bands are allowed to be used by a secondary network without harming the primary user operation. The impact of this empirical deficiency in spectral resource management has been aggravated with the exploding content consumption over wireless networks, and thus called for additional remedies. In 5G standards, Device-to-Device (D2D) communications and heterogeneous wireless networks are posed as two vital apparatus to alleviate this capacity crunch. In this work, we consider such an environment and analyze content delivery over satellite integrated CR networks. We propose a novel state-based and event-driven system model and investigate its behavior. We focus on throughput, energy efficiency and quality as key performance metrics, hence rendering the gains offered by D2D and satellite transmissions in this heterogeneous system.**

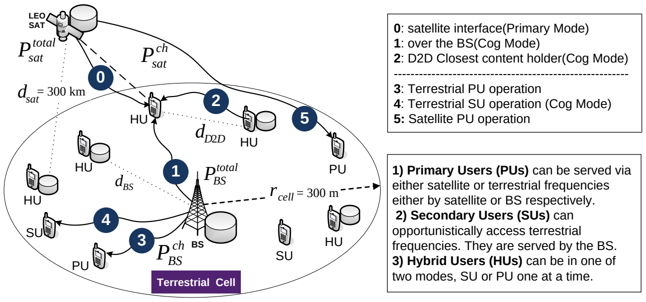
I. INTRODUCTION

Dynamic spectrum access and CR paradigm are posed as vital solutions and thus touted as capacity boosters for upcoming 5G wireless systems [1]. Given that mobile node density is drastically increasing, wireless nodes have high likelihood of having a peer device in close proximity in these emerging networks. Thereof, a different yet complementary solution is to exploit point-to-point close-proximity transmission, referred to as *device-to-device (D2D)* in 5G parlance. Moreover, drastic transition from host-centric to content-centric operation favors using the conglomeration of mobile devices as data providers [2]. Another approach facilitating higher capacity and improving coverage is to use multi-tier/multi-mode network structures with diverse scales ranging from femtocells to wide area satellite connectivity [3]. These two are complementary considering that D2D is proximity-oriented while multi-tier topologies enable long-range and large coverage transmissions.

In this work, we study the adoption of cognitive and D2D operation modes in an integrated terrestrial-satellite network for content-centric networking. Such a holistic system is yet to be explored in the literature. Moreover, content attributes such as being layered are considered as another novel endeavor. Thus, our main contribution is a novel model for layered content delivery over satellite integrated cognitive radio network (CRN). In addition, we investigate this system focusing on energy efficiency (EE), quality and throughput through extensive simulations, thereby highlighting the contribution of satellite and D2D connectivity in this multi-tiered network.

II. SYSTEM OVERVIEW

There are *satellite* and *terrestrial* segments in our model as shown in Fig. 1. The terrestrial segment is infrastructure-based with user devices having an additional D2D operation mode. We consider a single satellite coverage where satellite frequencies cannot be accessed opportunistically. In the system, there is one cell covered by a base station (BS). On the user side, there are three user types: PU, SU and HU. We focus on HUs since they facilitate multi-mode spectrum agility and thus the envisaged gains for higher efficiency. When they are in PU mode, they can be served by satellite frequencies over the satellite. When they are in SU mode, they can opportunistically access terrestrial frequencies that are served by either BS or another content holder HU. The resource allocation is done centrally by the BS that can detect PU, SU arrivals and departures, and allocate resources to HUs accordingly. For providing mobile content delivery with longer battery lifetime and smaller form-factor devices, it is imperative to attain EE in such a network. Thus, our motivation is to analyze this system for EE in addition to throughput and quality when content dissemination for mobile devices is the primary usecase.



0: satellite interface(Primary Mode)
1: over the BS(Cog Mode)
2: D2D Closest content holder(Cog Mode)
3: Terrestrial PU operation
4: Terrestrial SU operation (Cog Mode)
5: Satellite PU operation

1) Primary Users (PUs) can be served via either satellite or terrestrial frequencies either by satellite or BS respectively.
2) Secondary Users (SUs) can opportunistically access terrestrial frequencies. They are served by the BS.
3) Hybrid Users (HUs) can be in one of two modes, SU or PU one at a time.

Fig. 1. System model with network elements and operation modes.

A. Content and Traffic Model

A content is a self-contained chunk of video with features such as size and popularity rank. Contents can be cached at the satellite, BS and/or HU device(s) managed by Least Recently Used (LRU) replacement algorithm. When a content cannot be found in the local nodes, it can be provided from content repositories in other networks, i.e. "the universal source". The cache mechanism works as an in-network storage mechanism in satellite and BS.

Due to layered content concept, each content is either of type *base* or *enhancement*. Base contents are composed of standard components while enhancement contents have extra data for higher quality representation. Base contents have higher priority over enhancement ones. Content sizes are determined by exponential distribution configured with mean content size. PU and SU content requests are only of type

TABLE I
SYSTEM AND SIMULATION PARAMETERS.

Parameter	**Value**	**Explanation**
$N_{f_{sat}}$	5	Total number of satellite frequencies
$N_{f_{ter}}$	10	Total number of terrestrial frequencies
λ_{PU}^{sat}	0.15 $\frac{user}{sec}$	Arrival rate of PUs at satellite link
λ_{PU}^{ter}	0.8 $\frac{user}{sec}$	Arrival rate of PUs at terrestrial link
λ_{SU}^{ter}	0.5 $\frac{user}{sec}$	Arrival rate of SUs at terrestrial link
λ_{HU}	0.3 $\frac{user}{sec}$	Arrival rate of HUs at the system
W_{sat}	36 MHz	Bandwidth of satellite link
W_{ter}	2 MHz	Bandwidth of terrestrial link
f_{sat}	20 GHz	Frequency of satellite link
f_{ter}	700 MHz	Frequency of terrestrial link
$s(\hat{HU}, v_b)$	25 Mbits	Mean base content size requested by an HU
$s(\hat{HU}, v_e)$	5 Mbits	Mean enhancement content size requested by an HU
$s(\hat{PU^s}, v_b)$	25 Mbits	Mean base content size requested by a PU at satellite link
$s(\hat{PU^t}, v_b)$	25 Mbits	Mean base content size requested by a PU at terrestrial link
$s(\hat{SU}, v_b)$	25 Mbits	Mean base content size requested by a SU at terrestrial link
$Cache_{sat}$	32 Gbits	Satellite cache size
$Cache_{BS}$	8 Gbits	Base station cache size
$Cache_{Dev}$	200 Mbits	Hybrid device cache size
r_{enh}	0.5	The ratio of HUs that request both base and enhancement contents (ratio of high quality consumers)
u	1	Indicator for universal source existence, i.e. shows if a universal source is assumed and serves locally-absent contents
c_{HU}	920	Parameter showing added markup for configuring total number of HUs in the system setup
γ_s	0.9	The portion of idle satellite frequencies reserved for prospective PU arrivals

base whereas HU content requests can be both types. The request pattern is generated acc. popularity ranking modelled with Zipf distribution [4]. If an HU receiver is of high quality, after each successfully retrieved base content, it generates an enhancement content request. Due to PU appearance, HU content retrievals can be interrupted and then may continue from another content holder. For instance, HU starts retrieval from the BS at a terrestrial frequency. Once a PU appears, HU preempts that frequency and continues from the satellite.

B. System Dynamics

In our proposed state-based model, the system changes state in case of a user arrival or departure. At each change, current link state is updated accordingly.

1) PU arrival at the satellite link: If there are idle frequencies at the satellite link, PU is randomly allocated to one and the satellite link state is updated. If no idle frequency exists, PU is blocked and the satellite link state is not changed.

2) PU arrival at the terrestrial link: When no idle frequency exists at the terrestrial link, PU is blocked. If some frequencies exist with no PU activity, PU is randomly allocated to one and the terrestrial link state is updated. That frequency can be idle, have SU or HU in SU mode activity. If that frequency is idle, no preemption occurs. Otherwise, SU or HU in SU mode retrieving content from the BS or another HU device is preempted. For that preempted user, a new event is created. Through the new event, the preempted user will try to get the rest of the content. That content portion is not necessarily taken through the same link and from the same content holder. For each new generated event, the process starts from scratch.

3) SU arrival at the terrestrial link: If idle frequencies exist at the terrestrial link, SU is allocated to one randomly and the terrestrial link state is updated. Otherwise, the terrestrial link state is not altered and SU is either blocked, in case it is a new arrival, or dropped if it was preempted beforehand.

4) HU arrival: The overall HU arrival process is given in Figure 2. *FRM* stands for frequency reservation mechanism.

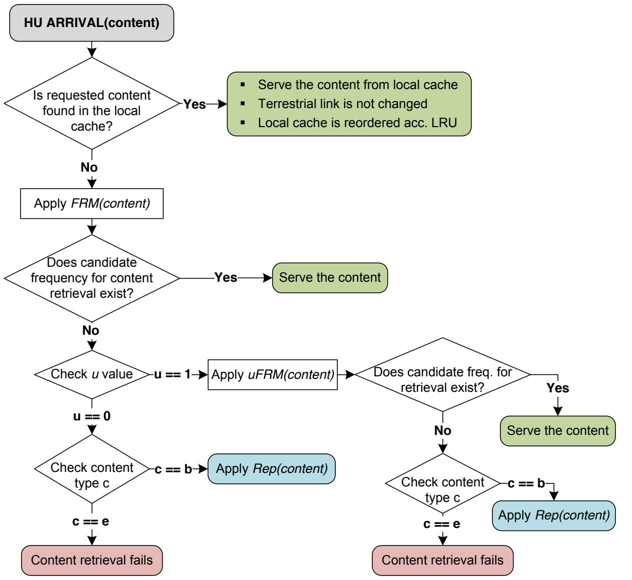


Fig. 2. Flow for HU arrival processing. (b: base, e: enhancement)

TABLE II
CONTENT LOCATIONS AND CORRESPONDING CANDIDATE FREQUENCIES.

Location	**Action**
Satellite	The idle satellite frequencies are taken to be candidate for content retrieval from the satellite. Note that not all idle satellite frequencies are taken to be candidates. As the satellite link is accessed by either PU or HU in PU mode in case of high HU activity, PUs will be blocked. To solve this problem, a portion of idle satellite frequencies (γ_s) are reserved for prospective PU arrivals.
BS	The idle terrestrial frequencies are taken to be candidate for content retrieval from the BS.
HU Device	The idle terrestrial frequencies are taken to be candidate for content retrieval through D2D mechanism.

The *FRM(content)* function operates as follows: If the content is found at some content holder, the corresponding idle frequencies are candidates for content retrieval. The candidate frequency selections are elaborated in Table II. The likelihood of choosing some candidate is determined by its preference coefficient r_x (our control variable for mode selection). Different preference coefficients of the satellite, BS and HU device(s) have impact on the performance and are design choices.

We illustrate the FRM operation with an example. Let $N_{f_{sat}}$=5 and $N_{f_{ter}}$=10. Assume there are three satellite idle frequencies ($idle_x^s = 3$), four terrestrial idle frequencies ($idle_x^t = 4$), and preference coefficients are $r_s = 1$, $r_{BS} = 2$ and $r_d = 3$. Assume the requested content is located at the satellite, the BS and some HU device, i.e. availability indicator $1_x^{c,s} = 1_x^{c,BS} = 1_x^{c,d} = 1$. The probability (preference) of getting content from the satellite is $\frac{r_s 1_x^{c,s} idle_x^s}{r_s 1_x^{c,s} idle_x^s + r_{BS} 1_x^{c,BS} idle_x^t + r_d 1_x^{c,d} idle_x^t} = \frac{1 \cdot 1 \cdot 3}{1 \cdot 1 \cdot 3 + 2 \cdot 1 \cdot 4 + 3 \cdot 1 \cdot 4} = 3/23 \cong 0.13$ where x is the current state. Denoting the weighted sum in the denominator of this fraction as $\bar{D}$, the probability of getting content from the BS is $(r_{BS} \cdot 1_x^{c,BS} \cdot idle_x^t)/\bar{D} = (2 \cdot 1 \cdot 4)/23 \cong 0.35$ and some HU device is $(r_d \cdot 1_x^{c,d} \cdot idle_x^t)/\bar{D} = (3 \cdot 1 \cdot 4)/23 \cong 0.52$.

In Fig. 2, we check for candidate frequency existence because "no candidate for content retrieval" situation can happen either due to the requested content being unavailable at a content holder or no idle frequency is available at some link. *uFRM(content)* function represents the universal

TABLE III
ENERGY MODEL PARAMETERS.

Name	Value	Name	Value	Name	Value	Name	Value
P_{sat}^{total}	240 W	$P_{dev}^{rec^{sat}}$	16 mW	P_{BS}^{idle}	0.3 W	$E_{D,sw(t)}^{tx}$	$\frac{24}{N_{f_{ter}}}$ mJ
P_{BS}^{total}	60 W	$P_{dev}^{rec^{ter}}$	8 mW	P_{BS}^{sleep}	0.12 W	$E_{D,sw(s>t)}^{rec}$	24 mJ
P_{sat}^{ch}	$\frac{P_{sat}^{total}}{N_{f_{sat}}}$	P_{dev}^{idle}	4 mW	$E_{D,sw(s)}^{rec}$	$\frac{8}{N_{f_{sat}}}$ mJ	$E_{D,sw(s>t)}^{tx}$	360 mJ
P_{BS}^{ch}	$\frac{P_{BS}^{total}}{N_{f_{ter}}}$	P_{dev}^{sleep}	1.6 mW	$E_{D,sw(t)}^{rec}$	$\frac{1.6}{N_{f_{ter}}}$ mJ	$E_{D,sw(t>s)}^{rec}$	24 mJ

frequency reservation mechanism and works as follows: If content retrieval from the universal source is initiated, the idle satellite or terrestrial frequencies are taken as candidate for content retrieval from the satellite or the BS, respectively. The likelihood of choosing some candidate is determined by its preference coefficient as explained in *FRM(content)* function. So the system decides on whether to retrieve the content from the universal source to the satellite or BS to serve from there. *Rep(content)* function will apply the replacement procedure which replaces some enhancement transmission with this more critical base content. The replacement can be applied only to terrestrial frequencies that are used for enhancement content retrievals from the BS or another HU device.

5) Departure: When any user departs from the system, we idle the used frequency. The corresponding link state is updated.

C. Energy Consumption Model

For EE analysis, our aim is to investigate the energy consumed per each successfully sent bit over the system. We therefore construct energy consumption models for HU devices and the BS. As the satellite is basically solar powered, we ignore its consumption. The energy consumption of an HU device and the BS entails the transmission (*tx*), idling (*idle*), and sleeping powers (*sleep*) while an HU device additionally consumes power for receiving content ((*rec*)). The energy consumption parameters for HU devices retrieving content from the satellite/terrestrial link, idling/sleeping of HU devices and the BS, HU device mode/frequency switching in Table III are integrated in the model. HU device wake-up energies for content transmission or retrieval are given in Fig. 3.

1) HU Device Energy States: In the energy model detailed in Fig. 3, we assume that HU devices initially sleep. They wake up to receive or transmit content shown by the transitions from State 1 to 2, 3 or 4 in Fig. 3. The relevant energy consumption is given on the transition arrow. Content transmission power is higher compared to content retrieval power. Content retrieval power via the satellite link is higher compared to the content retrieval power via the terrestrial link. For instance, if HU device wakes up to receive content from the satellite, it consumes $P_{dev}^{rec^{sat}} \times \Delta t_{rec}^{sat}$ energy shown as the loop State 2. After the content transmission or retrieval, HU device becomes idle shown by the transitions from State 2, 3 or 4 to 5. At State 5, HU device consumes $P_{dev}^{idle} \times \Delta t_{idle}$ energy for idling and looks up for the timeout duration ($< t_o^D >$). If the time expires, it goes into sleep as shown from State 5 to 1. Mode switching means the previous transmission or retrieval of a content was at some link (e.g. terrestrial) while the new one is at another type of link (e.g. satellite). Frequency switching means previous and new links are the same but content will be transferred through a new frequency. The energy of mode switching is higher compared to frequency switching.

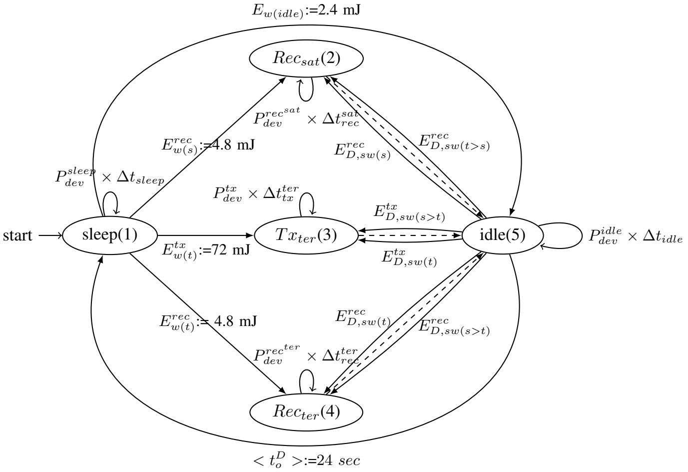


Fig. 3. HU device energy states. Dashed lines:transitions without energy cost.

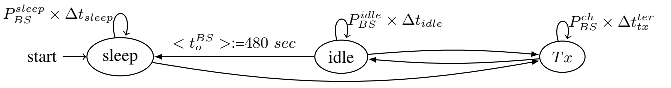


Fig. 4. BS energy states.

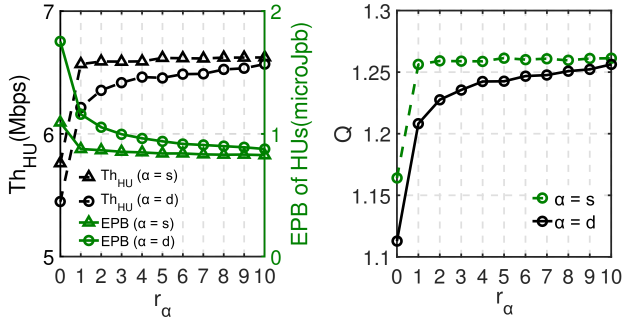
2) BS Energy States: We consider the sleep, idling and transmission components for calculating BS energy consumption given in Fig. 4. We ignore the costs of wakeup and switching since BS is usually in active mode for continuous operation such as controlling network modes and cognitive operation support. We consider the transmissions where the receiver is an HU device for the calculations. If all frequencies become idle, it transits to the idle state. It operates in timeout-based ($< t_o^{BS} >$) mode for going back to sleep state.

D. Content Quality Model

For performance investigation, we consider a streamlined quality model for the content quality experienced by the users for layered content operation. We avoid conforming to a specific coding standard and corresponding quality models to derive more general conclusions. Therefore, we rather adopt an abstract quality model. For each HU content request, we calculate a quality indicator value Q and then take its average over all content transmissions. If the base content is blocked or dropped, Q has value zero. If it is served, it has value one. Following a base content request, if there is a generated enhancement content, the portion of content size that has been transmitted successfully is added to the Q value from the corresponding base content. Note that if the base content is dropped, it has no contribution to the quality. However, the enhancement content has a contribution even if it is interrupted and partially transmitted. Thereof, $Q = 1_{[\text{base is transmitted}]} * (1 + 1_{[\text{enhancement generated} \wedge \text{not blocked}]} * \alpha)$ and $Q \in \{0\} \cup [1, 2]$ where α is the portion of successfully transmitted enhancement content and thus $0 \leq \alpha \leq 1$.

III. EXPERIMENTAL RESULTS

In the simulations, we consider non-time-slotted scheme. Our main goal is to analyze the baseline system performance. Hence, we do not focus on the sensing/transmission errors and waiting times/retrials. By the use of Friis and Shannon's



(a) Throughput and EPB. (b) Quality.

Fig. 5. Effect of increasing satellite and D2D preference parameters (r_s, r_d).

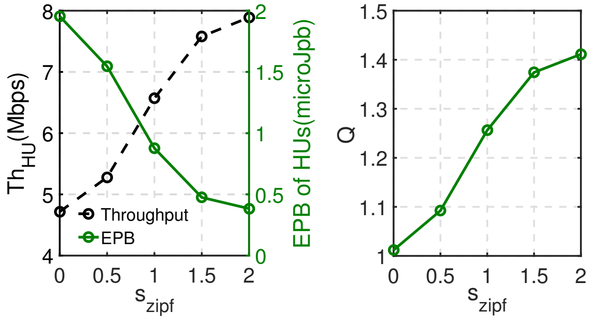
formulae, we get the received power strength of users that retrieve content from content holders and the channel capacities respectively. The parameters for the simulation are listed in Table I. For PUs and SUs, we do not focus on their specific physical locations. To calculate transmission rate, we take the half of the radius as the distance to the BS for PUs retrieving content from the BS and SUs. The traffic variability of PUs and SUs are achieved by exponentially distributed content sizes.

Note that N_{HU}=$N_{f_{sat}}$+2$N_{f_{ter}}$+c_{HU}, where N_{HU} is lower bounded in the system by $N_{f_{sat}}$ and $N_{f_{ter}}$ for Poisson arrival processes. The default resource allocation preference coefficients for the satellite, BS and an HU device are r_s=1, r_{BS}=2 and r_d=10, respectively. We investigate the throughput, energy consumption per successfully sent bit (EPB) and quality. The simulations are run 300 times per case for 1200 sec with 1000 distinct contents. The mean of these runs are reported. We perform experiments for varying satellite and D2D mode preference coefficients (r_s, r_d) and content popularity characteristics.

A. Effect of Mode Preference: Satellite or D2D

Once we integrate the satellite into our system, the throughput is increased due to capacity expansion via offloading as shown in Fig. 5(a). Larger r_s values make the satellite spectrum saturated for HUs since the longer service times in satellite links lead to higher channel occupation. Thus, the system does not improve further in terms of HU throughput in that upper range. As we preserve some frequencies for prospective PUs in the channel allocation scheme, this situation does not affect PU behaviour, i.e. CR principle of PU priority is protected. Considering EE, the performance characteristic is similar. Only BS and HU devices can provide content delivery for r_s = 0. Hence, by introducing the satellite into our system, some requests will be served by the satellite but will not result in significant energy consumption due to solar power used by the satellite. Accordingly, there is a quick improvement in EE as shown in Fig. 5(a) (from 1.1 μjpb to 0.8 μjpb). Note that increasing r_s further makes the satellite spectrum saturated for HUs. So, the EE performance is almost stagnant in further r_s range. With the introduction of the satellite into the system, there is also an improvement in the content quality as shown in Fig. 5(b) despite being less significant (from 1.16 to 1.26).

An increase in D2D preference r_d leads to shorter content transmission durations for HUs. Hence more requests can be served by the system, and the throughput improves as shown in Fig. 5(a) (from 5.4 Mbps to 6.6 Mbps). When the D2D activity is increased (larger r_d), devices consume less energy due to shorter links, leading to less energy consumption per successfully sent bit and thus EE improves as shown in Fig. 5(a). With increasing r_d, there is a significant improvement also in the content quality as shown in Fig. 5(b).



(a) Throughput and EPB. (b) Quality.

Fig. 6. Effect of increasing s_{zipf} value (changing popularity characteristics).

B. Effect of Content Popularity Characteristics

For content popularity modeling, the Zipf parameter s_{zipf} is used to change the popularity distribution among all contents in the system. The value s_{zipf}=0 means contents have the same popularity. With increasing s_{zipf}, the popularity differentiation increases. Thus, more popular contents are requested widely and hence they are cached in more HU devices. As shown in Fig. 6(a), the throughput of HUs improves from 4.7 Mbps to 7.9 Mbps with larger s_{zipf} values. EE is also substantially improved (from 1.9 μjpb to 0.4 μjpb) as more and more HU devices cache popular contents and the probability of finding those contents in own cache and at HU devices in vicinity increases. Accordingly, the boosted content transmission via D2D takes shorter time for the same amount of information, which leads to enhanced EE. When we increase s_{zipf}, the overall quality also improves from 1.01 to 1.41 as given in Fig. 6(b), which is intuitive due to higher throughput, opening transmission opportunities for enhancement layer contents.

IV. CONCLUSION

In this work, we have investigated content-oriented and satellite integrated CRN with layered content delivery. We have proposed a novel system model and performed simulation-based experiments for different settings of content popularity and mode preference for content retrieval while focusing on EE, quality and throughput performance.

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