Spectrum Sharing and Content-Centric Operation for 5G Hybrid Satellite Networks

Gürkan Gür
Zurich University of Applied Sciences (ZHAW)
Winterthur 8401, Switzerland
e-mail: gurkan.gur@zhaw.ch

***Abstract*—One key objective of 5G is to attain massive connectivity and 1000x capacity increase in wireless networks for serving data-hungry applications anytime-anywhere. In that vein, the role of hybrid satellite networks in 5G systems is deemed to be crucial with their core traits such as broadcast/multicast capability and ubiquitous connectivity. Another promising approach towards that goal is spectrum sharing where spectrum resources are extended to other similar networks or technologies to tackle with inefficient and inflexible utilization of radio spectrum. For networked applications, the impact of this empirical deficiency has been aggravated with the exploding content consumption over wireless networks, and thus called for additional remedies in 5G systems. In that regard, transformation of hybrid satellite networks towards a content-centric paradigm is essential. In this work, we consider how satellite networks are supposed to metamorphose for becoming an elemental player of 5G era and analyze two key dimensions for that goal: content-centric operation and spectrum sharing.**

I. Introduction

A key objective for 5G systems is 1000x capacity increase in wireless networks for serving data-hungry applications in heterogeneous and ultra-dense network settings. 5G vision is hard to realize with traditional wireless cellular network architecture due to insufficient flexibility and scalability. There is a need for disruptive solutions that can deliver more capacity while not increasing the cost of operation. In that regard, one key bottleneck is the spectral inefficiency inherent to exclusive spectrum use. Hence, spectrum sharing, especially in the form of cognitive radios to let radios access the spectrum dynamically by implementing agile and adaptive medium access, has been a main research direction for next-generation wireless networks to cope with spectrum scarcity (or underutilization) [1].

On the application side, content consumption oriented services entailing multimedia content are creating a huge and unprecented surge in network traffic. Accordingly, additional novel approaches in wireless networks complementing the spectrum sharing dimension are crucial [2]. An important direction for that advance is the integration of content-centric operation to 5G wireless systems embodied in Information-Centric Networking (ICN) architecture for Future Internet. ICN builds on the premise that the Internet usage has drastically evolved from a point-to-point communication and exchange paradigm to a content dissemination and retrieval context where content rather than network locations determines the protocol architecture and operation.

Integrated satellite and terrestrial networks is another key research topic in 5G networks since the cooperation of different wireless systems and multi-interface access enable design and runtime optimizations taking into account QoS requirements, signal quality (coverage), and network conditions [3]. Due to wide coverage, energy efficiency, support for mobility, backhauling capability, and central optimization capability, satellite networks are envisaged to be a critical element of 5G networks [4]. For instance, 5G technology will be largely concentrated in the population hotzones, thus 5G satellite networks will provide 5G services in remote regions where it is infeasible to operate a terrestrial network. This is also essential to mitigate new *5G Digital Divide* risks. Furthermore, satellite networks will have a symbiotic relation with other new technologies, namely D2D communications, mmWave, edge caching, for 5G deployments. Mutually, these will complement and also utilize each other for meeting the stringent 5G requirements. A specific use-case for these 5G hybrid satellite networks is the growing demand of broadband connectivity for internet-connected electric vehicles outside the dense urban areas.

The recent industrial developments also strengthen this impetus: SpaceX's Starlink project has begun satellite launches and is planned to include almost twelve thousand satellites when completed, while OneWeb launched its first 5G satellites in February 2019. In the same vein, Amazon's Project Kuiper aims to deploy more than three thousand satellites to cover areas where about 95 percent of the global population live [5]. These systems will interconnect and cooperate with terrestrial 5G systems. Thus, hybrid satellite networks[1] are regarded as an efficient and cost-effective facilitator for fulfilling 5G requirements [6]. However, for the realization of such converged networks, a multitude of issues pertaining to transmission efficiency, resource management, and mobility management have to be addressed [7].

Although there is large body of literature focusing on hybrid satellite networks, spectrum sharing (especially in the form of cognitive radios) or content-centric networks[2], they usually

This work was partially supported by the Scientific and Technical Research Council of Turkey (TUBITAK) under Grant 116E245.

[1]"Hybrid satellite networks" is a shorthand term for integrated space and terrestrial heterogeneous networks in this article.

[2]In this work, "content-centric" term refers to a "proposal-agnostic" ICN architecture where content (or information) is the key determinant for network architecture and protocols.

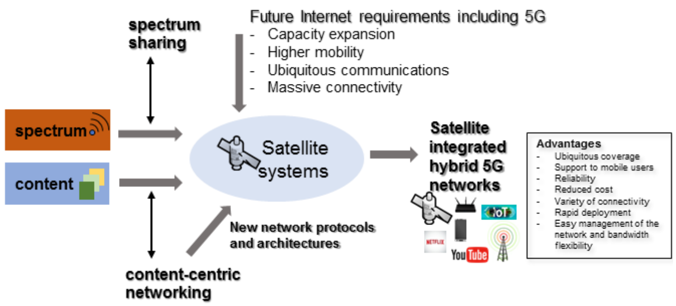

Fig. 1. Spectrum sharing and content-centric operation in 5G hybrid satellite networks.

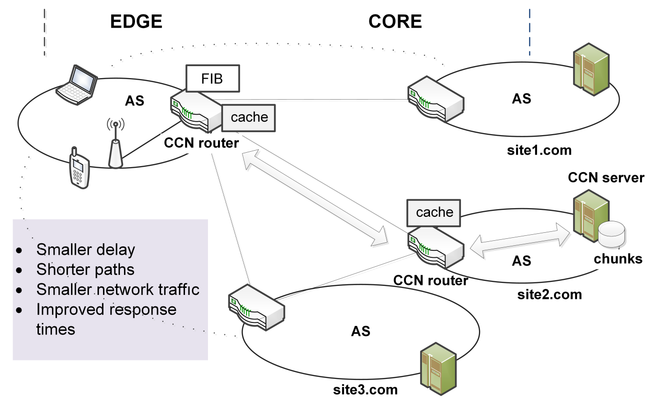

Fig. 2. An ICN example considered in CCN (Content-Centric Networking) proposal (AS, autonomous system; FIB, forwarding information base).

consider only a single aspect (e.g. CRNs) or a tuple of them (e.g., cognitive hybrid satellite networks or implementation of ICN in hybrid satellite networks). The intersection of content and spectrum sharing in satellite networks on the road to 5G is yet to be explored. Nevertheless, advances in these research directions are essential for the realization of 5G hybrid satellite networks as illustrated in Fig. 1. Satellite networks are going to be heavily shaped with these paradigms, which motivates us to investigate the prospects of such systems in this article. To this end, we discuss these approaches and elaborate on how they can be integrated with hybrid satellite networks in 5G. Albeit its merits, these networks also have their own challenges, which we also discuss later in the context of 5G.

Overall, our contributions in this work can be summarized as follows:

- We describe the key properties of 5G and hybrid satellite networks focusing on how the latter is instrumental to fulfill 5G requirements.
- We provide a concise overview on spectrum sharing followed by Future Internet concepts and content-centric operation in communication networks.
- We elaborate on how these two paradigms can be efficiently integrated with hybrid satellite networks.
- We analyze the prospects and challenges to realize the potential of spectrum sharing and content-centric operation in these hybrid networks, particularly for 5G systems.

II. Background

A. 5G and Satellite Networks

5G networked services are committed to provide fast content availability and uninterrupted operation to meet quality of experience expectations. Therefore, meeting the requirements of this heterogeneous setting calls for high flexibility in the network. This flexibility can generally be introduced in various ways (e.g., spectrally in time-domain or frequency domain) and at various entities in the network (e.g., end devices or the core network). Accordingly, radio itself needs to be agile, smart and adaptive as rendered by the spectrum sharing vision. Additionally, the network itself can provide flexibility by new paradigms such as software-defined networking (SDN) and Network Function Virtualization (NFV).

Satellite communications are expected to play an important role for 5G networks due to their inherent characteristics [8]. The most important factors leading to the diffusion of satellite communications into 5G, i.e. 5G hybrid satellite networks, can be summarized as ubiquitous coverage, support to mobile users, reliability, reduced cost, variety of connectivity, rapid deployment and easy management of the network and bandwidth flexibility. These systems are especially beneficial for mission-critical and industrial 5G applications where ubiquitous coverage and availability are essential.

B. Spectrum Sharing in Wireless Networks

The fundamental phenomenon leading to spectrum sharing is the "coexistence" of wireless networks. A coexistence scenario consists of at least two wireless networks or users which are in close geographical proximity such that the operation of one network avoids impairing the operation of another although that is possible [1]. Coexistence of multiple networks is challenging especially when these networks are of different types in terms of underlying technology or run by different operators. A key technology for spectrum sharing has been the cognitive radio concept which involves utilization of spectral resources in dynamic and opportunistic way without harmfully effecting the primary users [9]. There is a plethora of work on satellite networks with cognitive capabilities especially for core issues such as resource allocation or mobility regarding various emerging aspects such as green communications, heterogeneous settings and for applications such as multimedia traffic [9]–[11].

Spectrum sharing can occur in several domains: time, frequency, space, and code [1]. Usually, frequency domain gaps are primarily implemented: networks sense the spectrum and select the channel which hosts no other network. Existing schemes create coexistence gaps usually in one of these dimensions. A more ambitious option is to exploit multiple dimensions and increase the coexistence capability of a network in order to maximize spectral efficiency.

C. Content-Centric Operation in Networks

Content-centric operation of data networks has gained unprecedented importance with the migration of operational mode of Internet from end-to-end resource sharing to content access and consumption. An information-centric network is depicted in Figure 2. Due to the lack of connection-oriented paradigm, content-oriented networking can efficiently handle users' mobility and link/network disruptions. The utilization of extensive in-network storage for caching reduces delay and network traffic while improving content-based services. For instance, in mobile environments, "cache till you can transfer" enables higher network efficiency and availability for delay tolerant content services. These characteristics of content-centric architectures are intrinsically compatible with satellite network attributes.

Satellites have always been a fundamental element in content distribution enabling large-scale multicast/broadcast services [5]. In that regard, satellite networks are utilized for providing broadband services to fixed and mobile users especially in several scenarios where terrestrial networks cannot be used or are congested [4]. Although the content-centric re-architecting of satellite networks is a promising research topic for 5G and Future Internet, it is inadequately explored. Integration of this paradigm with spectrum sharing, which is elaborated in the next section, can break the barriers for hybrid satellite networks regarding content delivery in Future Internet.

III. Integration of Content-Oriented Operation and Spectrum Sharing in 5G Hybrid Satellite Networks

Integrated spectrum and content-centricity opens new possibilities for utilizing hybrid satellite networks in 5G systems. For successful integration, two important factors are flexibility and cost effectiveness. For the cost aspect, the development of more advanced terrestrial elements, especially user devices, and the "democratization" of satellite construction, deployment and launch services are envisaged to drastically improve cost effectiveness. Additionally, the cost of satellite components and cost per carried bit figure of satellite networks are also constantly decreasing with better hardware/algorithms and stronger competition. These trends are materialized in the recent planned 5G satellite network deployments listed in Section I. For the flexibility aspect, new hardware with more capable architectures, material advances, complex microelectromechanical systems and signal processing/PHY algorithms for adaptive operation are also opening new possibilities for spectrum sharing and content-driven services. To implement such a network, there are three system dimensions which pose major prospects to fulfill 5G objectives as explained in Figure 3 along with some fundamental research challenges as discussed in Section IV.

These dimensions should be jointly utilized in 5G hybrid satellite networks for meeting the performance requirements. In that regard, joint design of spectrum sharing and content centric operations is crucial since it can boost content delivery and spectral efficiency. For that purpose, cross-layer optimization techniques are promising. Moreover, to exploit performance gains in multiple dimensions, we need context-aware solutions that can identify which content is available/requested where and in which domains different systems can share the

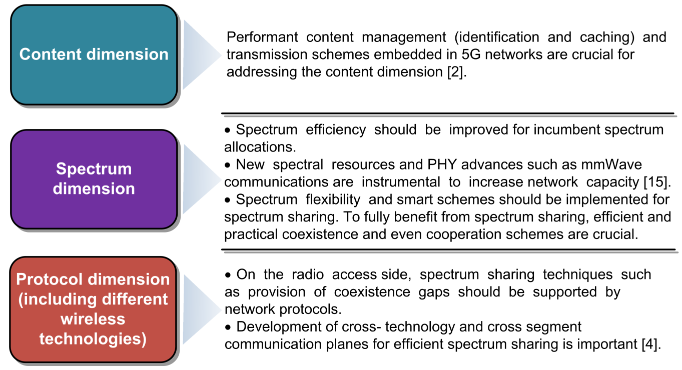

Fig. 3. System dimensions in 5G hybrid satellite networks.

spectrum with high throughput efficiency. Therefore, there are some key decisions for networks and radios to provide efficient and smart coexistence and content delivery. These range from very fundamental ones such as identifying the occupancy of a channel to more advanced and complex ones such as traffic analysis for exploiting spatial characteristics of spectrum occupancy and content availability.

IV. Prospects, Research Challenges and the Road Ahead

To realize 5G vision for integrated satellite and terrestrial networks, satellite capabilities are supposed to be substantially developed. Some key improvements are related to core aspects such as more advanced hardware, better resource management algorithms and agile radio technologies. From the practical point of view, any proposed mechanism for 5G must have affordable complexity and be suitable for implementation. Additionally, it must be scalable for dense network environments. For spectrum expansion, the radio front-end is supposed to listen to a wide range of frequencies; therefore radio hardware must be capable of sensing the spectrum in a wide frequency band. These requirements for satellites extend to other network elements in the converged 5G ecosystem.

An overall system view for a hybrid 5G satellite network with spectrum sharing and content-centric architecture is shown in Figure 6. The infusion of content-centric architecture requires protocol support as well as ubiquitous caching infrastructure. Additionally, terrestrial elements should be seamlessly integrated for a heterogeneous network architecture. On the spectrum front, spectrum sharing with a wider operating region is crucial. Although these are apparent enablers, utilization and coexistence of new techniques and their amalgamation towards high-performance 5G systems are not evident goals. In the rest of this section, we discuss these prospects which also layout research challenges for the development of 5G hybrid satellite networks.

A. Integration of Caches in Network Nodes

Receiver-driven model and caching are two salient features of ICN. Clearly, this approach benefits the delivery of popular content (e.g. reduced delivery delay) and alleviates resource requirements (e.g. bandwidth and server load) in the network.

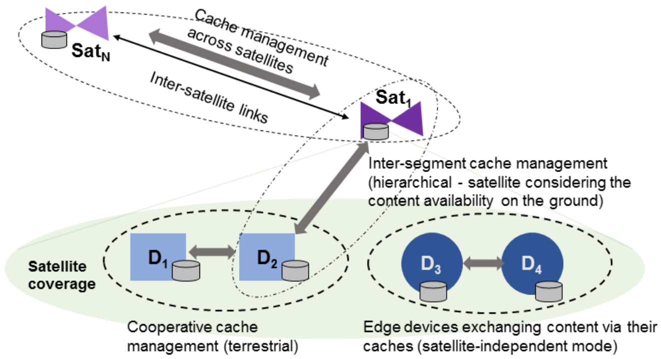

Fig. 4. Architectural aspects of caching in 5G hybrid satellite networks.

Thus, loose coupling between content and its originator provides opportunities to facilitate mechanisms for many of the prevalent issues with the current network architecture such as multicast, multipath routing and mobility. These advantages are also valid for 5G hybrid satellite networks considering the traffic characteristics driven by content-heavy services.

In content-centric networks, deployment of in-network caching at different points in a network is essential. However, conventional caching schemes are inadequate for 5G hybrid satellite networks [12]. The cache placement and management algorithms should take into account the broadcast nature, the single-hop access and large visibility of users in satellite networks (i.e. satellite-aware and adaptive cache management). There are also difficulties related to latency (especially for GEO satellites) and energy consumption for the return link to satellite [13]. Although the proximity to users is high in terms of hop count (usually a single hop) but low in terms of physical distance, the latter issue can be alleviated with a holistic caching approach integrating terrestrial elements and their caches. Obviously, this setting renders a more promising but complicated content-centric infrastructure.

Mobility of network elements should also be addressed in this environment. Spatial and temporal properties of user mobility may improve the caching performance since optimization of content placement and handovers is possible via mobility prediction. Furthermore, users can be utilized as "mobile data mules" via mobility-aware caching to disseminate contents in D2D mode [14]. This caching challenge involves also the mobility of satellites themselves. For non-GEO satellites, the served user devices constantly change due to trajectory of the satellites. To this end, inter-satellite links is an interesting research topic. The handover of content from neighboring satellites can provide a more efficient content delivery via calibration of "cache space" to the "user spatial distribution" [2] such as anticipatory cache pull over intersatellite links.

Overall, a cache management framework for 5G hybrid satellite networks should extensively exploit empirical information such as interest locality which refers to the correlation of requests and proximity of requesters. Therefore, a key capability is context-awareness in terms of users and services, leading to content-awareness for efficient personalized services [10]. Learning based caching schemes are promising in that regard [14]. For instance, tracking and estimation of timely content popularity in a predictive manner is possible using ML techniques such as reinforcement learning. Moreover, caching-oriented enhancements should be compatible with plain-vanilla ICN. As depicted in Figure 4, there are three architectural aspects for such a caching infrastructure which are described in Table I.

TABLE I
CACHING IN 5G HYBRID SATELLITE NETWORKS

Dimension	Explanation
Tiered caches	The satellite, terrestrial elements and user devices can form a hierarchical caching substrate. The satellite itself acts both as a central cache master with a large accessibility of user devices and as a feeder to terrestrial caches when cache misses occur for their connected nodes. That may involve inter-satellite cooperation between satellites using intersatellite links to exchange content or caching metadata such as content popularity characteristics.
Cooperative caches	Cooperative cache management in the terrestrial segment in connection with terrestrial infrastructural elements enables a more efficient cache operation exploiting interest locality in time and space. Moreover, shorter content transmission distances boost energy efficiency, which is crucial for mobile devices. Cooperative caching may yield major performance improvement for different metrics such as latency, throughput, and cost if it is designed to select the optimal subset of contents stored at the cooperative nodes [14].
Content-centric edge	The devices in the edge can store and share content in an ad-hoc setting independent from the satellite infrastructure. This operation mode is especially applicable to D2D communication schemes discussed in Section IV-C. It is beneficial to improve energy efficiency and decrease delay. However, finding spectral opportunities is a challenge, which further strengthens the case for spectrum sharing in these systems.

In general, caching closer (in terms of hop count or physical distance) to the consumer (in infrastructure elements or consumer devices) shortens the transmission path providing significant load reduction and smaller latency in the network. Additionally, hop count reduction implicitly provides substantial energy savings. However, these benefits can only become tangible in hybrid 5G satellite networks when some key factors are thoroughly considered for caching design as described in Figure 5.

B. Tighter Integration of Terrestrial Components

Integration between terrestrial and satellite components must be addressed at different levels, such as coverage, radio, terminal, spectrum, network and services, by ensuring seamless availability, diversity gain, portability and continuity across hybrid networks [4]. A potential research direction is on how to utilize frequency reuse between reconfigurable terrestrial backhaul links (intra-terrestrial sharing) and between the terrestrial and satellite segments (inter-segment sharing) [15]. This is also important for spectrum sharing discussed in Section IV-D.

The key change for the terrestrial segment in a content-centric spectrum-sharing hybrid satellite network is that

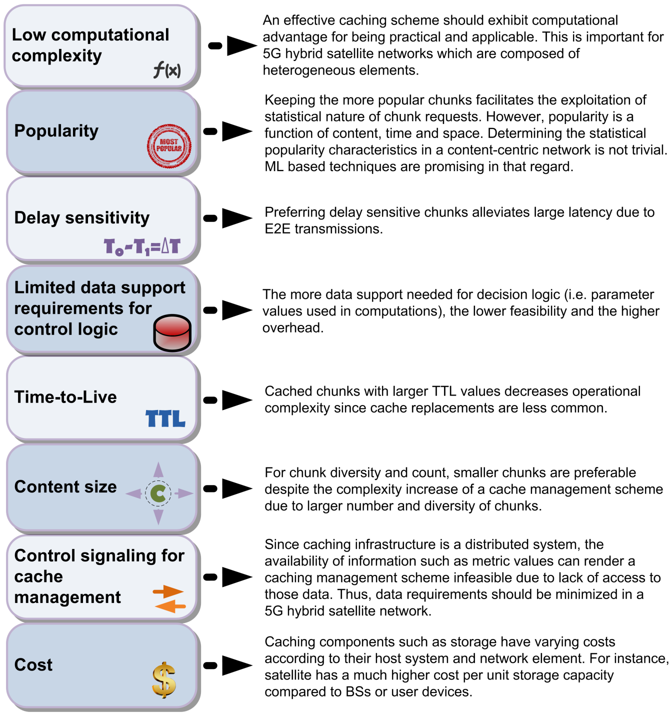

Fig. 5. Design factors on the caching infrastructure for 5G hybrid satellite networks.

content-centric operation requires switching to a new architecture with pertinent protocols. This is a multi-dimensional problem which involves the questions of adaptation of content-centric protocols and how to interface them with other legacy networks. For the terrestrial segment, there are also conventional questions reshaped by this new system. For multimode devices, network selection assisted by the infrastructure is more challenging due to content availability factor. This question is also related to how load balancing can be achieved between satellite, terrestrial elements and spectrum resources of other networks. For these functions and spectrum sharing discussed in the following section, efficient communication schemes between different systems are essential.

C. Optimization of Multihop Operation in the Realm of Content Consumers

An important approach facilitating higher capacity and improving coverage in 5G is to use D2D communications with multi-tier/multi-mode network structures. D2D communications are devised to improve spectrum utilization and overall performance enabling new peer-to-peer and location-based applications and services. It allows multihop content dissemination and can be optimized according to spatial and temporal availability of contents. It increases both spectral and content-wise availability for the network elements. It is also instrumental for 5G hybrid satellite networks. Although satellite provides a wide coverage, there are coverage holes and capacity limitations due to peculiarities of the satellite links such as limited bandwidth, physical impairments and shadowing/blocking. The key rationale of D2D communications is synergistic with the satellite (or any infrastructure-based connectivity) since it will improve the bitrates and service rates via short-range transmissions (i.e. joint optimization of satellite and terrestrial content delivery according to dynamic physical, link and network layer conditions). Moreover, it provides more flexible spectrum sharing since the radio environment is composed more of short-range transmissions leading to smaller interference regions compared to large-distance data exchange. This is especially beneficial in dense network environments envisaged in 5G and Beyond 5G networks.

The D2D mode can be boosted by utilizing "overhear-and-cache" capability provided by the broadcast nature of satellites. Terrestrial nodes can overhear and cache content in order to serve future requests of other nodes or itself in an anticipatory manner. However, how to locate content and exchange over D2D links is an important research challenge. For the connectivity services, gateway-based satellite network segments inherently provides a central cache (similar to HTTP proxies) which can be optimized according to user requests.

D. Spectrum Agility in Satellite Segment Extending to Terrestrial Infrastructure and Devices

For efficient spectrum sharing and agility across the entire integrated network, a diverse set of mechanisms should be employed[3]. In that regard, key technologies for 5G hybrid satellite networks can be listed as [11]:

- **Spectrum databases (a priori spectral knowledge)**: To be aware of the actual characteristics of incumbent users, databases storing information on incumbent transceivers such as WSDB are required. In scenarios where we need to sense the spectrum, a priori database knowledge of the channel occupancy could assist the spectrum sensing technique, increase the adaptation to spectrum changes, and save energy. Such information accompanied with Radio Environment Map (REM) data allows the designation of geographical zones where spectrum sharing is possible. Furthermore, mobility-aware spectrum sharing is instrumental with joint analysis of mobility prediction of users and a priori spectral knowledge. It enables learning for proactive spectrum access and predictive management of spectrum sharing based on user mobility. Such databases can be also fed and updated by satellite and terrestrial elements that are able to sense spectrum in a crowd-sensing manner.
- **Protocol enhancements**: Protocol enhancements for providing and/or exploiting coexistence gaps is a promising prospect but also an open challenge. Moreover, how to devise D2D enabling protocol extensions with satellite-terrestrial cooperation is another research topic. The design of cross-technology communication protocols is also crucial.
- **Spectrum Sensing**: Advanced spectrum sensing techniques exploiting recent and up-to-date information from multiple sources (sensors, historical data, external sources, etc.) are beneficial for performant spectrum sharing. Nevertheless,

[3] For inter-satellite spectrum sharing and cross-tier spectrum sharing, primary-secondary spectrum sharing is possible. However, this architecture can also enable fair spectrum sharing in unlicensed bands with satellites acting as spectrum access controllers based on location-marked spectrum DB and dynamically collected sensing results.

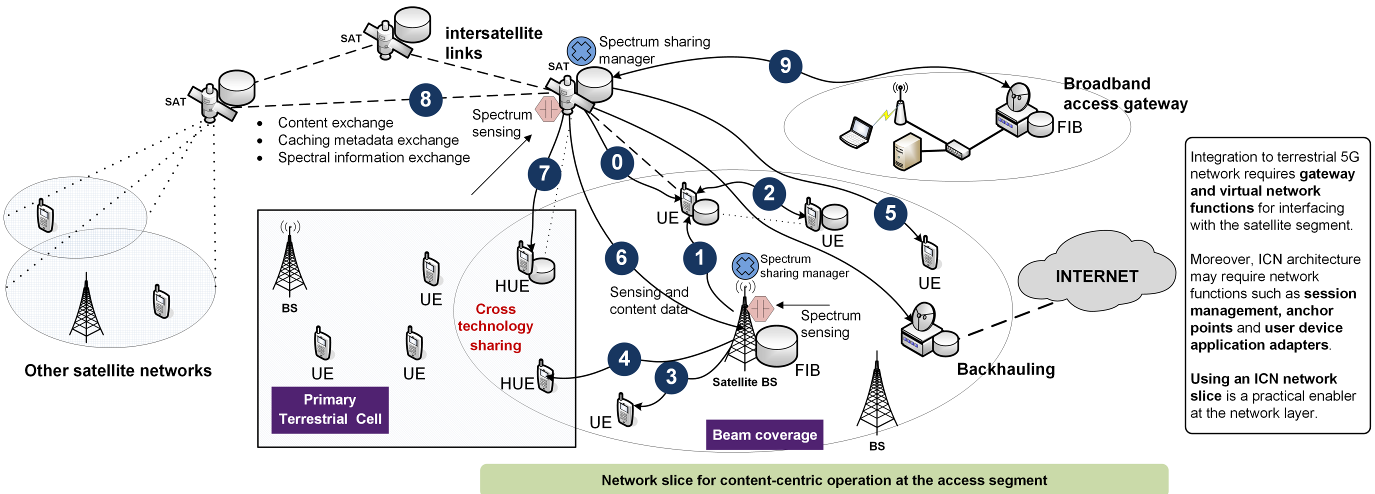

Fig. 6. 5G hybrid satellite network integrating spectrum sharing and content-centric operation. This architecture opens new possibilities in the terrestrial and satellite segments from the perspectives of spectrum expansion and content delivery. (0): through the conventional sat link, (1): through the satellite-integrated base station (SBS), (2): D2D content transmission, (3): served from the BS cache, (4): served by SBS via spectrum sharing with a terrestrial system, (5): a conventional User Equipment (UE) served via satellite, (6): sensing and content data sent to SBS, (7): a hybrid UE served by satellite via spectrum sharing with a terrestrial system, (8): inter-satellite data exchange (content, spectral info, caching metadata), (9): UEs served by a satellite gateway.

how to access and integrate these data is not evident in a hybrid network.

- **Beamforming**: Beamforming can be applied for spectrum sensing/interference detection or for improving the Signal-to-Interference plus Noise Ratio (SINR) of the satellite terminals. Interbeam interference is a limiting factor of the frequency reuse in multibeam satellites. It can be detrimental for both conventional transmissions and spectrum sharing in the terrestrial segment. Moreover, it degrades the spectrum reuse due to D2D mechanisms. Therefore, beam adaptation mechanisms for position, size and transmission parameters are still important research challenges.
- **Cooperation (among satellites and cross-technology)**: A fundamental approach for better spectrum sharing is to facilitate cooperation in communication systems. For instance, cooperation via inter-satellite links for exchange of spectrum occupancy information, cached data and caching metadata can significantly improve system performance. In the terrestrial segment, infrastructure elements can exchange spectrum sensing data or interact with other dynamic spectrum access system such as TV White Space (TVWS) for better environment-awareness.
- **D2D communications**: Utilization of spectrum sharing in D2D communications is another research direction. In that vein, terrestrial components can opportunistically exploit spectral gaps (in time and space) for content dissemination. They can also be assisted by satellites in the large scale(beam-level) and the terrestrial infrastructure in the small scale(cell-level).

Terrestrial 5G has substantially increased the range of frequencies where it can operate in relation to prior systems, including mmWaves. Moreover, new satellite systems are being designed to utilize higher frequencies for tackling with crowded spectrum landscape. Therefore, the spectrum agility in the envisaged network should be accompanied with going to higher frequencies such as Ku and Ka bands for capacity expansion in addition to utilization of conventional satellite frequencies such as L-band and C-band [11]. New mmWave communication bands and techniques are promising for that purpose similar to terrestrial 5G systems. To cope with the channel impairments such as severe attenuation, Adopting on-board antenna arrays can help with mmWave signals, and can also enable multi-beam transmissions.

E. Satellite as a Spectrum Sharing Enabler

Real life network environments are more heterogeneous and complicated than the current spectrum sharing research addresses. For example, in contrast to simple settings of two co-located networks, there may be many different technologies from different network operators in practical settings. For spectrum sharing in hybrid networks, satellites can provide the following capabilities:

- **Single point of decision**: Satellites with their inherent broadcast and multicast capabilities can be used not only as a policy updater but also as a policy maker for spectrum sharing. Satellites having a wide footprint depending on their orbital height (i.e. LEO, MEO or GEO) aggregate wide knowledge about the users and networks in its service region. Moreover, supporting complex settings of 5G dense and heterogeneous deployments requires more than statically-defined rule-based schemes. Satellites with their terrestrial counterparts can dynamically optimize and configure policies for spectrum sharing. Since spectrum utilization can differ geographically, satellite can jointly utilize location-based sensing and less dynamic spectrum DB information for zone-based decisions. Additionally, in hybrid 5G networks, the optimization can be executed by spectrum sharing managers in a tiered way to avoid coarse decisions for spectrum access: either on the satellite or on

TABLE II
RESEARCH CHALLENGES AND QUESTIONS FOR 5G HYBRID SATELLITE NETWORKS

Challenge	Phenomena	Key questions
The location of spectrum sharing control	Different rules of operation, different ethics, inadequate integration	- What is the optimal location of spectrum sharing control logic? - The design of distributed management of spectrum sharing policies in different network tiers
Protocol enhancements for spectrum sharing	Lack of support for spectrum sharing in current satellite network protocols	- Can coexistence gaps be facilitated? - How to devise D2D enabling protocol extensions with satellite-terrestrial cooperation? - The design of cross-technology communication planes?
Joint optimization of spectrum and cache management	The multidimensional optimization space for content and spectrum management	- How to optimize spectrum management and content caching jointly? - Lightweight heuristic based joint optimization for spectrum sharing-content caching - The design of cooperative caching mechanisms
Network architecture and protocol evolution for ICN	The requirement of content-centric operation in 5G hybrid satellite networks	- How to deploy ICN into hybrid satellite networks? - Network softwarization techniques (e.g. network slicing) for enabling content-centric operation - What are the necessary modifications to standard ICN protocols?
Power asymmetry	High-power systems vs. small-cell/low-power systems	How to improve network identification and power management for opportunistic radios in coexisting satellite and terrestrial networks?
Lack of communication among co-existing networks	Networks controlled by different operators using different technologies	How to facilitate cooperation with minimal communication?
Physical distances	Large physical distances between satellite segment elements and terrestrial elements	How to alleviate the inherent physical distance issue for the space segment?
Better sensing algorithms	Heterogeneous network elements and hybrid architecture under impairments such as shadowing, mobility and channel impairments	- How to address physical layer impairments? - How to design cooperation algorithms? - Optimization of decision techniques such as machine learning based schemes? - Integration of incumbent DSA systems such as TVWS for performance improvement?
Cooperation frameworks	The need for cooperation among diverse network elements and segments	- Which cooperation algorithms are suitable for this dynamic network environment? - What should the level of cooperation be? - How to achieve secure cooperation (e.g. for caching)? - Advanced cost-benefit analysis for cooperation algorithms?
Spectrum expansion for hybrid spectrum-sharing satellite and terrestrial networks	The need for incorporating new frequency bands (e.g mmWaves) with 5G	- Which spectrum bands are more favorable for spectrum sharing regarding satellites? - How to tackle with sensing challenges for the new spectrum bands?

the terrestrial base station with a more local view as shown in Figure 6.

- **Spectrum sensing and monitoring**: Basically, a radio with cognitive capabilities for spectrum sharing can sense its environment, and make a set of measurements with its special sensors. Upon collecting environmental information, it can control operating parameters. For spectrum sensing, satellite-based methods using multibeam antennas in large coverage areas are possible. This information can be enriched with a priori data from databases, sensing data from other satellites through intersatellite links or terrestrial sensor elements on the ground.

F. Putting it All Together

Considering these prospects and issues, there are various challenges and research directions which are detailed in Table II. In addition to those peculiar questions, some meta-challenges are chiefly related to the feasibility and viability of content-centric and spectrum sharing hybrid satellite networks in practical settings:

- **Complexity**: Low complexity regarding network design, protocols and algorithms is necessary for cost-efficient and practical content-centric hybrid networks. This issue is especially relevant for the space segment with limited computational and storage resources.
- **Resilience**: Satellite may become the single point of failure as more and more functions are driven by the space segment. This issue is more pronounced compared to the more distributed spectrum sharing environment in general terrestrial systems. Moreover, spectrum sharing can depend on external data, which may be unavailable or corrupt in some circumstances. Cooperation mechanisms can also degrade resilience due to dependence on communications and external inputs.
- **The level of change in legacy systems**: The concepts brought by content-centric operation and spectrum sharing are to be implemented in incumbent systems. There is a direct relation between the extent those systems are changed and the cost incurred. However, the envisaged benefits are only possible with substantial evolution. This is a fundamental trade-off to be investigated for these integrated satellite and terrestrial networks. Network softwarization is an important enabler since content-centric operation can be facilitated in a network slice with software-defined networking in 5G.
- **Scalability**: The scalability of 5G hybrid satellite systems is difficult to achieve due to heterogeneity and size of the envisaged network. For instance, unlicensed spectrum sharing based on crowd sensing is more challenging in this fragmented environment. Optimized network architectures are to be investigated for diverse requirements. The level of coupling between different segments can induce significant overheads.
- **Where to implement spectrum sharing logic?**: The location of decision framework and its architecture (centralized vs. distributed) is a general spectrum sharing problem which is also valid for 5G hybrid networks.
- **Security and privacy**: This aspect refers mostly to general challenges already in effect for these technologies.

Although content-centric operation and spectrum sharing are promising for implementing the requirements of 5G in hybrid satellite networks, the practical viability of these schemes are to be established with further research efforts considering these research challenges and questions.

V. Conclusions

In this work, we have provided some insights on how content-centric operation and spectrum sharing can collectively drive realization of 5G objectives in hybrid satellite networks. We believe that these paradigms will steer the role of satellite networks in the Future Internet and 5G ecosystem. Furthermore, we have identified and discussed prospects and research challenges for satellite and terrestrial integrated networks in that setting.

References

[1] Y. Han, E. Ekici, H. Kremo, and O. Altintas, "Spectrum sharing methods for the coexistence of multiple RF systems: A survey," *Ad Hoc Networks*, vol. 53, pp. 53 – 78, 2016.

[2] T. D. Cola and A. Blanco, "ICN-based protocol architectures for next-generation backhauling over satellite," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

[3] G. Giambene, S. Kota, and P. Pillai, "Satellite-5G integration: A network perspective," *IEEE Network*, vol. 32, no. 5, pp. 25–31, September 2018.

[4] G. Araniti, I. Bisio, M. D. Sanctis, A. Orsino, and J. Cosmas, "Multimedia content delivery for emerging 5G-satellite networks," *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 10–23, March 2016.

[5] K. Holt, "Amazon plans to launch thousands of internet satellites," https://www.engadget.com/2019/04/04/amazon-internet-satellite-network-project-kuiper/, accessed 2019-06-26.

[6] 3GPP, "Study on scenarios and requirements for next-generation access technologies," TR 38.913, v.14.3.0 Release 14, Mar. 2017.

[7] T. Taleb, Y. Hadjadj-Aoul, and T. Ahmed, "Challenges, opportunities, and solutions for converged satellite and terrestrial networks," *IEEE Wireless Communications*, vol. 18, no. 1, pp. 46–52, February 2011.

[8] K. Liolis, N. Chuberre, I. Andrikopoulos, and M. Piccinni, "On a future internet architecture augmented by satellite networks," in *2010 Future Network Mobile Summit*, June 2010, pp. 1–8.

[9] E. Biglieri, "An overview of cognitive radio for satellite communications," in *2012 IEEE First AESS European Conference on Satellite Telecommunications (ESTEL)*, Oct 2012, pp. 1–3.

[10] Y. Kawamoto, Z. M. Fadlullah, H. Nishiyama, N. Kato, and M. Toyoshima, "Prospects and challenges of context-aware multimedia content delivery in cooperative satellite and terrestrial networks," *IEEE Communications Magazine*, vol. 52, no. 6, pp. 55–61, June 2014.

[11] D. Tarchi, A. Guidotti, V. Icolari, A. Vanelli-Coralli, S. K. Sharma, S. Chatzinotas, S. Malekil, B. Evans, P. Thompson, W. Tang, and J. Grotz, "Technical challenges for cognitive radio application in satellite communications," in *2014 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, June 2014, pp. 136–142.

[12] L. Galluccio, G. Morabito, and S. Palazzo, "Caching in information-centric satellite networks," in *2012 IEEE International Conference on Communications (ICC)*, June 2012, pp. 3306–3310.

[13] A. Detti, A. Caponi, and N. Blefari-Melazzi, "Exploitation of information centric networking principles in satellite networks," in *2012 IEEE First AESS European Conference on Satellite Telecommunications (ESTEL)*, Oct 2012, pp. 1–6.

[14] S. Wang, X. Zhang, Y. Zhang, L. Wang, J. Yang, and W. Wang, "A survey on mobile edge networks: Convergence of computing, caching and communications," *IEEE Access*, vol. 5, pp. 6757–6779, 2017.

[15] X. Artiga, M. A. Vazquez, A. Perez-Neira, C. Tsinos, E. Lagunas, S. Chatzinotas, V. Ramireddy, C. Steinmetz, R. Zetik, K. Ntougias, D. Ntaikos, and C. B. Papadias, "Spectrum sharing in hybrid terrestrial-satellite backhaul networks in the Ka band," in *2017 European Conference on Networks and Communications (EuCNC)*, June 2017, pp. 1–5.