The 'C' Trinity

- Converged, Cross-layer and Cooperative Integration of Satellite Communication System

Su Gao, Yufei Shen, Ying Tao, Houtian Wang, Na Zhou, Zhicheng Zhou
Institute of Telecommunication Satellite,
China Academy of Space Technology,
Beijing, China
E-mail: 15712889970@163.com

***Abstract*—Application is the driving force of system evolvement. Satellite communication has seen its progression based on service provisioning capability and user experience. In this paper, we present an 'integrated' next-generation architecture, providing global users seamless connectivity, improving quality of service, and achieving synergy by robust network design. Satellite plays an important role in various aspects of our system. Techniques, such as powerful regenerative onboard processing, multi spotbeams with tunable structure, tailored frequency plan and flexible intersatellite links, etc., enable satellites with remarkable competence. Based on these, converged satellite-terrestrial network, cross-layer protocol stack and cooperative robust framework, as a trinity, together accomplish the integration of satellite communication system.**

Keywords-integration; satellite; communication; converge; cross-layer; cooperative.

I. INTRODUCTION

People appreciate the profound impact that modern wireless communication brings to us, while expecting more influential pervasion to all aspects of our daily life. Ubiquitous architecture distributing wireless services will become prominent in the next generation system [1]. It is important to design an interface for seamless connectivity while users change from terrestrial to satellite network, and vice versa. In addition, the system needs to consider and compensate deficiencies caused by various transmission environments. The protocol needs to be optimized to overcome deficiencies of the current separate structure, which is accomplished by cross-layer design. Furthermore, from the macrostructure point of view, the overall system performance needs to be promoted by applying suitable system engineering methods, on the basis of the above converged and Quality of Service (QoS)-based cross-layer design. To boost overall performance, cooperative strategies should be designed to combine information provided by different links in order to reduce data redundancies and improve transmission efficiency [2].

The remaining of this article is organized as follows. Section II portrays the system architecture we considered and illustrates converged, cross-layer and cooperative integration concepts. Section III describes integration challenges and solutions. Section IV concludes this article.

II. SYSTEM ARCHITECTURE

The system architecture is portrayed in Figure 1. Note this is a generalized system illustrating concepts in our discussion.

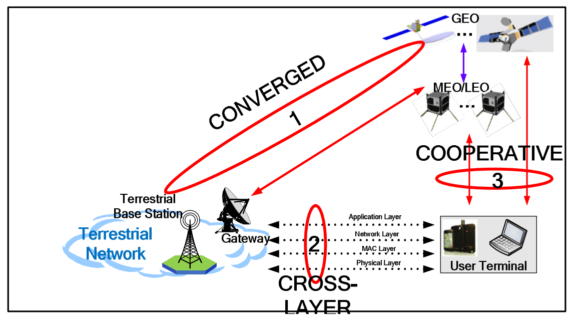

Figure 1. System Architecture

The system includes:

- Terrestrial network: well-established ground-based communication system. Base stations connect user terminals with traditional communication model. Here, the figure only shows a simplified layered framework including application layer, network layer, Media Access Control (MAC) layer and physical layer. These layers will be used in our discussion in the following sections.
- Satellite gateway: communicates with satellites via feeder links. In the figure, the gateway is shown within the terrestrial network but it does not have ground cell network communication functionality.
- Space segment: contains satellites. This framework does not target any particular satellite constellation type. The satellites are assumed to be bidirectional interactive, with transparent structure or OnBoard processing (OBP) capabilities. Satellites can provide mobile or fixed satellite communication service. Geosynchronous Earth Orbit (GEO) satellite can either carry deployable antenna for mobile users or generate C/Ku/Ka band multi-beams to produce broadband services. Medium Earth Orbit (MEO)/ Low Earth Orbit (LEO) satellite constellations may vary and have a certain design in the following sections. InterSatellite links (ISLs) are assumed.

 ISBN: 978-1-61208-545-6

- User terminals: are interactive. Terminals have access to satellite and terrestrial networks. Terminals may be fixed or mobile.

According to the analysis in the previous section, our system is designed as an integrated one. The integration is considered in three dimensions. First, to bridge the digital divide, converged integration is carried out in the interface dimension, providing seamless connectivity and effective merge between satellite and terrestrial networks. Second, to optimize QoS metrics, cross-layer integration is carried out in the protocol dimension, overcoming deficiencies of the current separate structure by joint modeling of different layers in the protocol stack. Third, to boost overall performance, cooperative integration is carried out in the link dimension, achieving synergy among transmission links for higher throughput and network robustness.

Each of the three integrations over three different dimensions solves one aspect of the system deficiencies according to user experience. They also reflect the sequence while optimizing the system: providing seamless connectivity for all users is the first step, followed by improving quality of service, and overall performance advancement brings all the users the best communication experience. These three integrations, which together form our design guidelines for satellite communication system, are a trinity.

III. Integration Challenges and Solutions

In this section, we discuss various integration issues in detail.

A. *Converged Integration*

This is the first guideline of unifying the system. The converged integration considers the interaction and interface design of satellite and terrestrial networks which is mainly reflected in radio interface design. It will be seen from our discussion that satellite design plays an important role as the satellite ability and performance affects various aspects of the converged interface.

1) *Radio Interface and Satellite Design*

To improve satellite communication capability and reduce system deployment cost, satellite design advancement plays a key role in aerospace systems. Therefore, it largely influences performance of the unified satellite-terrestrial system and its air interface design. An integrated solution should reflect satellite characteristics and modify the air interface design accordingly. For voice services, flexible transformation and routing onboard enabling the satellite to support single-hop communication among user terminals gives better service quality; for broadband access services, advanced antenna techniques can produce multiple and movable spotbeams providing users dynamic service management. All these satellite technology advancements inspire radio interface design to better satisfy user requirements.

In this subsection, we present an example that user and system requirement leads the satellite design, and how novel satellite ability affects radio interface architecture. We consider GEO mobile communication satellites carrying unfurlable antenna, which gives greater equivalent isotropic radiated power (EIRP) for ground users to have better receiving gain. This type of large diameter mesh antenna, together with the feed array, generates multiple spotbeams to achieve seamless coverage for a large number of users, where each beam can cover hundreds of square kilometers.

This new characteristic brings some design issues for mobile radio interface design. Due to variation of space environment and mechanical insensitiveness, the antenna oscillates, resulting in the satellite antenna pointing inaccurately during the oscillation lifecycle [3]. From the user experience point of view, this phenomenon mainly influences system performance and radio interface design in two aspects: synchronization and interruption. The first one affects communication system in various layers and is the basis in establishing the phone call for a single user. The second one guarantees the basic QoS during the phone call and usually measured in system level as interruption probability of the whole network. These two aspects are the most important aspects for users in the network and directly connected with users' communication experience, thus are essential in analyzing the effects of antenna oscillation to radio interface design.

2) *Interruption*

Radio link failure is the main reason of interruption. When errors occur, messages cannot be received successfully and certain system parameters are reset. Then, the radio link failure occurs and communication is interrupted [4].

Network interruption needs two conditions to happen, the location condition, where the user must be located at the edge of some beams, and the time condition, where the interruption must occur during the communication process. These two conditions are independent so can be analyzed separately and combined together as the whole interruption probability. To reduce interruption probability, two methods may be applied:

- Design channel allocation strategy according to time and frequency of antenna oscillation. The receiving C/N can not only be increased but also be more stable, thus guaranteeing sufficient and stable link budget.
- Modify terrestrial telecommunication protocol by increasing the number of re-transmissions of access channel and paging channel. This can reduce the probability of error as the probability that antenna oscillation causing the failure of multiple transmissions is reasonably low.

3) *Satellites in the Future Converged System*

It can be seen from previous discussion that radio interface design issues such as synchronization and interruption are closely related to satellite characteristics such as deployable antenna oscillation. It is important to investigate satellite antenna structure to know more about the oscillation process in various circumstances [1]. It is also important to design a tailored control strategy based on the

 ISBN: 978-1-61208-545-6

satellite bus's ability to maintain position and attitude of the spacecraft to ensure satellite position is not changed by the oscillation.

Not all future satellites are equipped with deployable antenna. Some of them provide Ka broadband services and with multiple spotbeams. They allow tunable power level and dynamically changeable EIRP to reach balanced receiving power among users. Other characteristics include digital payload with onboard processing, advanced frequency reuse and optical intersatellite links, etc. These advanced techniques [1] make the convergence of satellite system to the mature terrestrial radio interface easier, but at the same time introduce new issues specifically applicable to satellite transmission such as channel environment and long transmission delay, which urges modifications to the terrestrial network.

B. Cross-Layer Integration

Cross-layer design is essential for wireless system design and has already been widely used in terrestrial communication systems [5]. It plays a key role in optimizing QoS metrics. For an integrated satellite communication system, the upper layer design uses the cross-layer concept. We mainly consider two aspects: cross-layer design of radio resource management and network layer routing. In the following, a generalized optimization model is given and the mechanisms to solve it are analyzed according to characteristics of relevant parameters. As an example, network layer routing optimization problem is simulated. It can be seen from the discussion that for this dimension of integration, more powerful satellites are required.

1) Optimization Model

To improve the robustness of satellite communication networks and realize better performance in a dynamically changing communication environment, cross-layer design should be carried out and models should be built to optimize the relevant cost function in the considered layer. Other layers' parameters should be included as constraints so that the optimization problem contains the whole system's impact, thus forming an integrated design solution.

The current trend toward the migration to satellite-terrestrial integrated services opens new opportunities for cross-layer system design [6]. Designing an efficient, reliable and flexible resource allocation or network routing mechanism in satellite networks has always been a big challenge. Cross-layer optimization can integrate the layers of the protocol stack into a comprehensive classification framework, which can meet the requirement of QoS in satellite networks. The cross-layer architecture proposed is shown in Figure 2.

2) Solvable Mechanism

It should be noted that balance should be found between computational complexity and optimality, i.e., in a multiple-access/network scheme with few parameters, few degrees of freedom are left to resource/routing optimization, whereas including lots of parameters and constraints may result into computationally unaffordable approaches. Therefore, the application of optimization model to resource management and network routing in satellite communication networks need to be reasonable and feasible. In addition, a computationally and numerically solvable mechanism of the model is essential. It depends on system characteristics and model properties.

For resource allocation, slots allocated to the user terminal are integer in satellite networks. So the problem of cross-layer dynamic bandwidth resource allocation can be solved by transforming the optimization model into a nonlinear integer programming problem, which is more accessible.

For network routing, optimization is usually to provide a set of numbers, paths, destinations, etc. Integer programming is not suitable for this type of problem and dynamic programming needs to be applied. Take ant colony method [7] as an example. The process of ants looking for a path is similar to path discovery process from source to destination. There are two kinds of agents in this type of method: forward agent and backward agent. The basic idea is that the former travels through the satellite networks and collects routing information and the latter updates the routing table. When data packets are sent from the source satellite and reach an intermediate satellite, this satellite node will forward them according to the routing table. The process continues, until data packets reach the destination. The key idea is that a set of routes needs to be found during each step of the mechanism, so the optimization model is transformed into a dynamic programming problem.

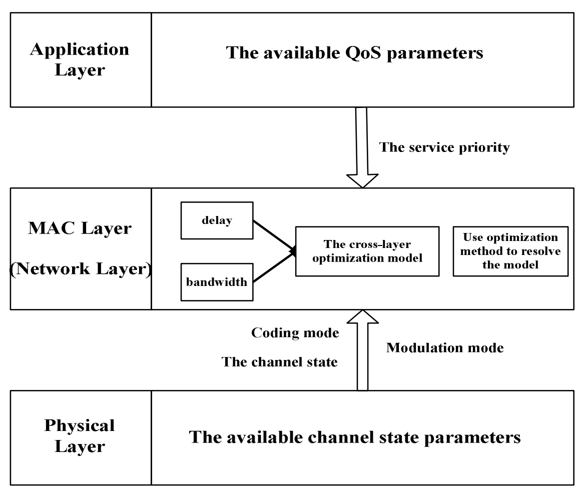

Figure 2. Cross-Layer Optimization

3) Simulation Results

In this part, we consider network routing as an example to explain the advantage that cross-layer design brings. The performance of a model designed based on the above idea, Cross-layer design and Ant-colony optimization based Load-balancing routing algorithm for LEO Satellite Networks (CAL-LSN) [8] is studied. Note that although the method is designed for LEO, it can be transferred into a network with hybrid constellation.

 ISBN: 978-1-61208-545-6

The simulation model is shown in Figure 3. An iridium-like satellite constellation is considered with two intra-plane ISLs (namely, links to the adjacent satellites in the same orbital plane) and two inter-plane ISLs (that is, links to the neighbouring satellites in the right-hand and left-hand orbital planes). While intra-plane ISLs are maintained for the whole satellite period, interplane ISLs are broken as satellites come close to the poles due to adverse pointing and tracking conditions, when satellites move to lower latitudes, inter-plane ISLs are re-established. Moreover, cross-seam ISLs, namely links between satellites in counter-rotating orbits, are not used.

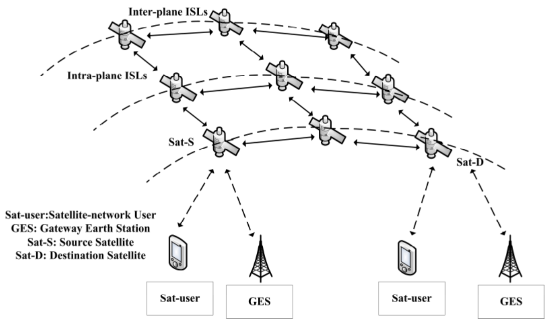

Figure 3. Cross-layer simulation model

The methods proposed in [9] and [10] are chosen to compare with CAL-LSN. The reason to choose these two algorithms is as follows. In [9], an adaptive routing algorithm based on an Improved Ant Colony System (IACO) was made use of in LEO satellite networks. The authors improve the original ant-colony algorithm in LEO satellite networks with its own cyclical and regular characteristics. In [10] the Distributed QoS-based Algorithm (DQA) was proposed. This algorithm is also based on ant-colony system. To meet QoS requirements minimum bandwidth constraints are also considered in DQA.

We first compare the performance of the receiver's throughput when CAL-LSN, DQA and IACO are utilized in the satellite networks. Figure 4. (a) shows the comparison. The reason why CAL-LSN has the highest throughput is that it can collect information from the physical layer. Comparing with DQA and IACO, the throughput is about 6.32% and 7.53% higher when CAL-LSN is used.

The average utilization of all inter- and intra-satellite links over the whole constellation is also compared between the above mentioned three strategies. We can see from Figure 4. (b) that although IACO improves the original ant-colony algorithm, it does not consider the influence of the residual bandwidth on QoS requirement. CAL-LSN has the same trends as DQA as the user number increases but has better performance. Comparing with the other two algorithms, the link utilization is the highest when CAL-LSN is used. It is about 6.52% and 29.24% higher comparing CAL-LSN with DQA and IACO respectively.

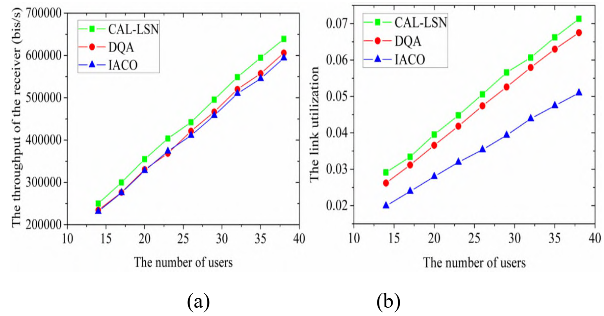

Figure 4. Throughput and link utilization comparison

4) *Satellite Design Issues*

Cross-layer design brings a system with better performance in a dynamically changing communication environment. However, it also brings some challenging issues to satellite design. When the converged satellite-terrestrial system is built, layered design guideline and cross-layer optimization of terrestrial wireless network is introduced to satellites, making the space segment system more complicated [2].

First, the cross-layer design of satellite constellations requires ISLs with high transmission capacity while satellites needs a flexible pointing adjustment mechanism. Interplane ISLs are difficult to maintain when satellites come close to the poles due to adverse pointing and tracking conditions. Second, powerful onboard processing capability is required for computational complex tasks. However, signal processing onboard need to be flexible to some extent for dynamically changeable tasks, so advanced and flexible payload structure such as channelization and software defined radio (SDR) may be applied. Third, constellation design should be investigated to make network routing and resource management more efficient and realizable.

C. *Cooperative Integration*

Cooperative integration is the last dimension in our architecture and mainly aimed at increasing network robustness. It is on the basis of converged satellite-terrestrial and cross-layer QoS-based integration, which were discussed in the above sections. By applying cooperative strategies, data redundancies are reduced and transmission efficiencies are improved, thus allowing more users in the network with better QoS. In this section, cooperative diversity to use multi-path in receiver is first discussed followed by network coding which mixes different data flows to save resources. We again present satellite design issues as a final remark.

1) *Cooperative Diversity*

In satellite communication system, the satellite-to-ground channel is a typical fading channel. In order to assure the communication quality, efficient technology to defeat wireless fading is necessary. The advantage of diversity technology on improving the impact of channel fading gradually attracts attention. By sending the same signals through several independent paths and adopting a

 ISBN: 978-1-61208-545-6

combination technology at the receiver, the power of the received signal is significantly enhanced.

Cooperative diversity technology in ground wireless communication system has been well studied. In satellite cooperative communication system, we investigate three cooperative strategies according to the processing scheme at relay satellite: amplify-and-forward (AF) scheme, decode-and-forward (DF) scheme and coding cooperative (CC) scheme.

We simulate the performance of the outage probability for the above satellite cooperative diversity scheme. Outage probabilities for satellite cooperative diversity are illustrated in Figure 5. Meanwhile, the performance of non-cooperative system is also provided for comparison. The readers may refer to [11] for theoretical modeling and deviation. The simulation and analytical results of outage probability are mostly coincident. We can also see that:

- Satellite cooperative diversity schemes lead to considerable improvement on the outage probability compared with the non-cooperative system. Among these three cooperative strategies, CC achieves the lowest outage probability.
- As SNR increases, the outage probability of AF and CC schemes decreases faster than that of the DF scheme. The DF scheme outperforms the AF scheme when the SNR is low, but becomes inferior at high SNR. This is because when SNR is high, transparent satellite structure in AF introduces less noise and the decoded scheme becomes less effective.
- The outage probability under urban scenario is greater than that under suburban one. However, the performance of DF scheme under these two scenarios seems similar.

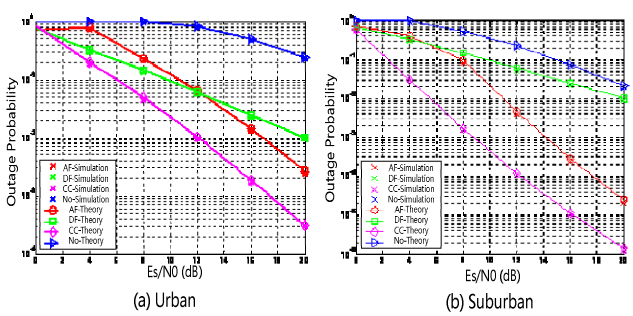

Figure 5. Cooperative diversity outage probability under urban and suburban scenarios

2) Network Coding

The basic idea of network coding is to allow conflict and combination of several data packets on the same time slot or the same frequency band. A network node receiving such a signal should broadcast the processed data, in order to assist the data recovery at other network nodes. We design network coding architecture for various applications:

- Transparent transmission satellite system: the satellite and the ground station are connected through a feeder link and the combination of them forms the relay node in the network. The satellite is equivalent to antenna of the relay node and ground station is responsible for signal processing.
- On-board processing satellite system: such complicated processing procedure is difficult to implement using today's satellite ability. However, complexity can be reduced if reliable coding techniques are applied with some loss of link performance.
- Relay satellite system: for an application where ground relay is used, the received signal can be transmitted to ground station regardless whether the satellite has the onboard processing ability or not. The signal can be encoded by the ground station and transmitted to user terminals. However, to complete the communication process, terminals communicating with each other must be located in the coverage area of the same ground station or the ground station can be interconnected through the network.
- Satellite systems with inter satellite links: a virtual relay channel can be formed by many satellites communicating with each other. In this case, design of resource scheduling algorithm is very important.

The above discussion assumes a three-point model. We now present design ideas of network with many points where many data streams are transmitted. In this case, corresponding routing and resource management algorithms are important. From the above discussion, we know that, if data transmitted between two nodes is equivalent, PNC technology can be used to save resources. In real communication system, there are many unidirectional links and many relay nodes serving different communication links. Moreover, even communication link is two-way, data transmitted in the two directions is not equal. In this case, virtual communication links that data transmitted in two directions can be constructed by designing corresponding scheduling algorithm, so that PNC technology can be used by this link to save resources [12].

3) Satellite in Cooperation

The cooperative strategy in our discussion above forms the third dimension of integration. Similar to the previous two, the cooperative integration ability in satellite communication systems is closely related to satellite performance [2].

- The satellite is always used as an active component instead of a transparent medium; thus, a regenerative structure is necessary in many scenarios. However as analyzed above, demodulation, decoding and parity information regeneration put heavy burden on satellite and raise challenges in on-board processing design.
- In advanced multi spotbeam satellite system, it was mentioned in [12] that the system does not perform well, as it requires the downlink beam to cover both satellite terminals. The likelihood of this situation is

 ISBN: 978-1-61208-545-6

lower for multi spotbeam satellites. However for other applications as multicast, channel independency is a key element for reaping the benefits of network coding multicast.
- From the simulation results, we can also see that cooperative strategy performs differently in various channel conditions. So, satellite payload that can adapt to channel conditions is essential for users to receive consistent service.
- Satellite mechanism enabling effective synchronization plays a key role in engineering realization in lots of cooperative scenarios.

IV. CONCLUDING REMARKS

Satellite communication has seen evolvement in recent years according to service provisioning requirements while global ubiquitous connectivity is on the way. Following this trend, our research considered system integration in three dimensions. Converged integration in interface dimension bridges the digital divide with satellite-terrestrial co-design providing seamless connectivity. Cross-layer integration in protocol dimension optimizes users' service quality with joint modeling of different layers in the protocol stack. Cooperative integration in link dimension promotes performance for all users by improving overall network robustness.

Our discussion revealed that satellite, in various aspects, plays an essential role [2] in the integrated system design.

- Powerful onboard processing capability based on advanced telemetry and command design is needed for computational complicated integration tasks, though a transparent structure can be used in some applications.
- Flexible regenerative structure should be applied to further reduce burden and adapt to variable channel conditions.
- Multi spotbeam techniques with dynamically allocation capability provide tunable structure for multiple users, which are useful in future broadband systems.
- Tailored frequency plan and frequency reuse schemes based on beam design should be applied to provide sufficient carrier to interference (C/I) ratio.
- Intersatellite link (ISL) giving intraplane and interplane connectivity needs flexible pointing adjustment mechanism, thus requires satellite mechanics innovation.
- Telemetry, command and other communication workforce onboard guarantees effective synchronization in various application scenarios.

In conclusion, future satellite communication system providing universal service requires satellite-based design throughout its construction [2]. It is thus possible to maximize the system capacity at present, make use of the benefits brought up by technical development and accelerate the accomplishment of newly integrated satellite communication system.

ACKNOWLEDGMENT

This paper is supported by the National Natural Science Foundation of China (Grant No. 91438205, 61675232).

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 ISBN: 978-1-61208-545-6