SATELLITE AND SPACE COMMUNICATIONS **SSC**

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SSC Newsletter **Vol. 21, No. 2, Dec. 2011**

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The Satellite and Space Communications (SSC) Committee is a volunteer group actively involved in advancing satellite and space communication technologies within the IEEE. This committee is approved by the IEEE Communications Society and is governed by the constitution and bylaws of the IEEE as well as the other twenty-three Technical Committees in the Society. The committee belongs to the Technical Committee Clusters of Communication/Signal Processing (C/SP).

SATELLITE & SPACE

- JOIN US -

All conference attendees are welcome to join us in the SSC Committee meeting.

Location: Room 337 of the Hilton

Date: **Wed. Dec. 7th, 2011**

Time: **12:00 - 13:00**

Future SSC Meetings

June 2012, Ottawa, Canada.
Dec. 2012, Anaheim, CA, USA.
June 2013, Budapest, Hungary

GC2011 SSC Committee Activities:

Symposium on Selected Areas in Communications:

- *Thursday, 8 December 2011 • 8:00 – 10:00*

Location: GRB 342 C.
SAC12 Satellite Coding and Transmission Systems
Chair: Enzo Alberto Candreva, University Of Bologna, Italy.

- *Thursday, 8 December 2011 • 13:30 – 15:30*

Location: GRB 342 C.
SAC13 Satellite and Space Communications Controls
Chair: Takaya Yamazato, Nagoya University, Japan.

- *Thursday, 8 December 2011 • 16:00 – 18:00*

Location: GRB 342 C.
SAC14 Satellite and Space Networking
Chair: Giovanni Giambene, University of Siena, Italy.

If you like to join SSC Technical Committee: Please send your name and e-mail address to the SSC Secretary, optionally include your mail address, telephone and fax numbers.
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MESSAGE FROM THE CHAIR

Prof. Nei Kato

This is the third time I convey my message in this column as the Chair of Satellite and Space Communications (SSC). First I would like to share with you a good news that for ICC'12 SSC area, we have received 54 submissions which representing the highest numbers for recent ICC/GC conferences. I would like to thank our SSC members for your positive contributions and also I would like to express my appreciation for the great efforts our vice chair Dr. Igor Bisio has made. Without his dedicated solicitation and excellent management, this would not have happened. With more submissions, more papers will be accepted for the conference which means our area in flagship conferences ICC/GC are evolving into a more desirable place for information exchange regarding satellite communication technologies.

I want to take this opportunity to simply explain the activities between technical committee of satellite communications of IEICE of Japan and KOSST of Korea. We have jointly held JC-SAT (Joint Conference on Satellite Communications) for many years.

The JC-SAT has been held every year in Japan or Korea from the year of 2000, the conference intends to provide a forum for researchers in satellite telecommunications field to discuss the current status, technical challenges, standards, fundamental issues, future services, and applications. JC-SAT conference covers technologies and system implementations of satellite communications as they relate to the areas of fixed, mobile and broadcasting satellite services. This year, the JC-SAT2011 will be held in Nagoya, Japan on Dec. 12-13, 2011 with prominent researchers from Korea, Canada and China.

Now we have planned a special issue of IEICE Transactions on Communications, entitled "Special Section on Satellite Communication Technologies in Conjunction with Main Topics of JC-SAT2011". This special section aims at timely dissemination of research in these areas with possible topics include, but are not limited to:

- Satellite communications (fixed-satellite communications, mobile satellite communications, inter-satellite communications, deep space communications);
- Satellite broadcasting (BS, mobile broadcasting);
- Satellite-ground integrated communications system;
- Satellite sensor network;
- Others on the elementary technologies, the system technologies, and the applications concerning the above topics.

As the Guest Editor-in-Chief of this special issue, I would like to invite you to submit your contributions. For detailed information, please refer to:

http://www.ieice.org/eng/s_issue/cfp/2012_11EB.pdf.

The submission deadline is 16th March, 2012.

Finally I would like to thank you again for your support and I am looking forward to seeing you in IEEE GC'11.

Prof. Nei Kato, Chair
Satellite and Space Communications Technical Committee

SCANNING THE WORLD

Dr. Igor Bisio

I would begin my third "*Scanning the World*" article by expressing my gratitude to our Chair, Prof. Nei Kato, for his kind words, reported in his "*Message*", about the result obtained by the *Satellite and Space Communications* (SSC) Area of the *Selected Areas in Communications* Symposium of the conference IEEE ICC'12.

As our Chair wrote, it received 54 submissions; globally the Symposium received 160 papers. Our area represents the 33% of the overall submissions to the Symposium composed of other 5 areas (Access Network, E-health, Powerline Communications, Smart Grid and Tactical Communications).
Obviously, this satisfactory result is due to the fruitful contribution of our scientific community including both members of our committee and other researchers in the field of satellite and space communications and networking, which I would deeply thank.

In the following part of this article, I would briefly survey a framework that represents a trendy research area due to the importance that it may have in the daily life of people: *Pervasive Communications and Computing*.

The general concept of *Pervasive Communications Environment* (PCE), known in the literature, is based on multi–modal access to integrated communications infrastructures that have text, audio, video, and voice capabilities [1]. It may alter the dynamic of human interactions and enable dynamic and complex forms of cooperation and collective action. From the technical viewpoint, the PCE paradigm envisages a world where a wide set of quantities - such as vibrations, heat, light, pressure, magnetic fields, human behavior - are acquired through sensors and transmitted through suitable seamless communication systems for information, decision, and control aims.

On the other hand, new media devices such as smartphone, portable computers, and digital recording devices, link people into a larger increasingly and integrated communication infrastructure, broadly known as the Internet, encouraging a larger pervasive communication environment.

In this context, satellite communications may be very important. Since 80s, R. L. Harvey from the Lincoln Laboratory of the Massachusetts Institute of Technology (USA), guessed it in [2]. In fact, he addressed the critical technical issues about waveform design, spacecraft technology, satellite launch options and costs.

If on one hand, today, most of the problems he highlighted have been fixed, on the other hand, new challenges are now open. In this sense, a recent inspiring paper [3] has been provided by one of our Past Chairs, Prof. Mario Marchese. He described the necessary interdisciplinary advances required in the PCE field such as new communication and networking solutions, less complex operating systems, miniaturized memory, innovative algorithms, efficient signal processing, and context-aware solutions.

These solutions, he wrote, are aimed at creating networks of heterogeneous devices that communicate seamlessly so connecting *anything, from anyplace, at anytime*. These are the common keywords of the satellite and space communications research field: it implies adding to the classical problems (QoS, mobility and security) the peculiarities of PCE such as intermittent connectivity, disruptive links, variable delays, and high bit error rates.

These problems, from my viewpoint, represent fascinating challenges of our area, which may contribute in several applicative scenarios where monitoring and connecting the physical world is important: civil protection, transportation, underwater, space monitoring and tele-medicine, among others.

The last mentioned field, the tele-medicine, is a very important example of the impact of pervasive communications realized by satellite systems. In facts, satellite broadband communication technologies offer wide-area broadband connectivity for telemedicine applications, even in remote areas and isolated regions where the terrestrial technologies suffer [4].

These application areas and the mentioned research challenges may constitute interesting fields of cooperation and new research topics for our scientific community.

Dr. Igor Bisio, Vice Chair
Satellite and Space Communications
Technical Committee

[1] Toward a Pervasive Communication Environment Perspective by Ted M. Coopman, First Monday, Volume 14, Number 1-5, January 2009.

[2] The Critical Satellite Technical issues of Future Pervasive Broadband Low-cost Communication Networks by R. L. Harvey, Acta Astronautica, Volume 7, Issue 10, October 1980.

[3] Interplanetary and Pervasive Communications, IEEE Aerospace and Electronic Systems Magazine, Volume 26, Issue 2, February 2011.

[4] Pervasive E-health Services Using the DVB-RCS Communication Technology by Demosthenes Vouyioukas, Ilias Maglogiannis and Vasilios Pasias, Journal of Medical Systems, Volume 31, Number 4, April 2007

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FORTHCOMING GLOBECOM AND ICC CONFERENCES

COSPONSORING / RELATED CONFERENCES AND WORKSHOPS

ICC 2012
June 10-15, 2012, Ottawa, Canada.
http://www.ieee-icc.org/2012
Since 1965 the IEEE International Conference on Communications has been one of the flagship conferences of the IEEE Communications Society. IEEE ICC brings together the world's leaders, scientists, policy makers from industry and academia. The IEEE Ottawa Section is proud to host IEEE ICC 2012 Conference and Exhibition from 10-15 June 2012 where recent advances in the field of communications will be presented.
The theme of the conference is “CONNECT • COMMUNICATE • COLLABORATE”. For participants it promises to stimulate the scientific exchange of ideas, the identification of future trends in communications, and the illumination of business opportunities. The conference program will feature 12 technical symposia, 16 industrial forums, keynote presentations, several workshops, and tutorials.

MILCOM 2012
Oct. 29 – Nov. 1, 2012, Orlando,FL, USA
http://www.milcom.org/
MILCOM 2012 is soliciting unclassified and classified (up to DoD Secret) technical papers as well as proposals for tutorials and panels on current topics of interest such as communications and information processing systems, social networking for military applications, weapons, and battle-space technologies. Professionals in industry, academic, and government organizations from the U.S. and countries worldwide are encouraged to contribute and participate in addressing the latest technology in trusted communications, situational awareness, and decisive action.

GLOBECOM 2012
December 3-7, 2012, Anaheim, CA, USA
http://www.ieee-globecom.org/2012
IEEE GLOBECOM 2012 will feature a comprehensive technical program including 12 Symposia and a number of Tutorials and Workshops. IEEE GLOBECOM 2012 will also include an attractive industrial and forum program featuring keynote speakers, various Business, Technology and Industry fora, and vendor exhibits. Prospective authors are invited to submit original technical papers for presentation at the conference and publication in the Proceedings. Proposals for Tutorials, Workshops, and Fora are also invited. Visit the IEEE GLOBECOM 2012 website, http://www.ieee-globecom.org/2012, for details and submission information.

CONFERENCES CALENDAR

CONFERENCE	DATE & LOCATION	INFORMATION
IEEE Aerospace Conference 2012	Mar. 3-10, 2012 Big Sky, MT, USA	http://www.aeroconf.org
WCNC 2012 IEEE Wireless Communications & Networking Conference	April 1-4, 2012 Paris, France	http://www.ieee-wcnc.org/2012
CITS 2012 2012 International Conference on Computer, Information and Telecommunication Systems	May 13-16, 2012 Amman, Jordan	http://congreso.us.es/cits2012/
6th ASMS 6th Advanced Satellite Multimedia Systems Conference & 12th Signal Processing for Space Communications Workshop	Sept 5 - 7, 2012 Baiona, Spain	http://www.asms2012.org/
International Conference on Localization and GNSS	June 25-27, 2012, Starnberg, (Munich), Germany	http://www.icl-gnss.org/2012
SPECTS 2012 International Symposium on Performance Evaluation of Computer and Telecommunication Systems	July 8-11, 2012, Genoa, Italy	http://atc.udg.edu/SPECTS2012
18th Ka and Broadband Communications Conference 2012	Sept. 24-27, 2012, Ottawa, Canada	http://www.kaconf.org
ICSSC 2012 International Conference on Satellite and Space Communications	Sept. 26-28, 2011 Rome, Italy	http://www.waset.org/conferences/2012/rome/icssc/
ITST-2012 11th International Conference on Telecommunications for Intelligent Transport Systems	Nov.5-8, 2012, Taipei, Taiwan	http://www.itst2012.org

To all SSC members: If your postal address, telephone or fax numbers have changed, please update them with the committee secretary. You can review our current records on our web page at http://committees.comsoc.org/ssc/.

Opportunities for Network Coding in Satellite Networks

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***Abstract* — Network coding benefits in terms of throughput, delay, and security are well characterized for variety of applications and networks, ranging from wireline networks to wireless sensor networks and robust mechanisms for distributed storage. Beyond traditional broadcast and multicast applications, we present opportunities for network coding to enhance satellite networks by exploiting the capabilities of end terminals to receive and process several, possibly heterogeneous transmission routes. Emphasis is given to the throughput, delay, resiliency and robustness of (i) multi-beam satellite systems with overlapping beams and terminals with multiple beam reception capabilities, (ii) LEO and GEO satellites which provide soft-handover for high-speed vehicles, and (iii) convergence of multiple satellite and terrestrial networks. At the core of our solutions lies a resource allocation problem that takes into account the load (traffic demands) per user, system constraints, topology, and channel conditions. Network coding is seen as an enabler of these mechanisms, allowing a seamless and efficient exploitation of the multiple, available paths by having (i) source nodes that manage and control the transmission of linear combinations of data packets through heterogeneous communication routes, and (ii) intermediate nodes at each route that can generate new coded packets with opportunistic storage.**

***Index Terms* – Network coding; Multi-beam satellites; Converged Satellite Systems.**

I. Introduction

Satellite systems enjoy a set of key features that make them valuable for broadband communication and content-delivery services in a variety of applications ranging from disaster scenarios, where the terrestrial infrastructure is compromised, to provision of services in rural areas or developing countries, where terrestrial infrastructure may be scarce or absent. These features include the ability to support a large terminal population as well as independence from terrestrial infrastructure and almost ubiquitous coverage. More recently, different types of aircraft (e.g., commercial airplanes, autonomous aerial vehicles) and network infrastructure on the ground are being incorporated to help respond to higher demands for rate, coverage and robustness. Interconnection of heterogeneous networks in space, ground, and possibly in the air brings with it the potential to enrich functionalities, and services to the end users by providing more complex topologies than the traditional relay or one-hop scenario of satellite systems. Aiming to exploit the limits of these creates a new challenge to appropriately allocate and manage these inherently diverse resources. Given the dynamic nature of i) traffic demands and system requested loads, ii) communication channels, and/or iii) the location of the nodes of the network, a key opportunity to improve capacity and Quality of Service (QoS) to end users lies in exploiting interactions and multiple, available routes. At the crux of this problem lies a resource allocation issue, where flexibility and adaptability to changing traffic demands can be achieved.

Network coding is proposed as an enabling technology for i) seamlessly exploiting the multiple routes available to each terminal, and ii) providing an additional and efficient network-level erasure (loss) protection mechanism. The former relies on the fact that any coded packet (for a sufficiently large field size) is useful towards decoding the original data, thus requiring no mechanisms to track and manage the transmission of individual packets sent through the different beams. The latter allows the system to increase redundancy to compensate for packet losses without requiring a repetition of the packets on several routes at the network layer, as would be the case in current systems, e.g., for soft-handovers, or as a key complement to Automatic Repeat request (ARQ) mechanisms at higher-layers. Network coding constitutes a disruptive paradigm [1], [2] that relies on mixing (coding) of packets at intermediate nodes in the network, rather than storing and forwarding them, as in traditional routing schemes. In fact, it can provide robustness against packet losses and proven throughput optimality in multicast scenarios [3], which makes it attractive for satellite communications for improving throughput, delay and robustness for terminals.

Our contribution is to characterize various scenarios, beyond classical multicast and broadcast services, that can exploit these enriched topologies and network coding capabilities. In particular, we focus on the challenges and opportunities for i) load balancing current and future multi-beam satellites, ii) soft-handover mechanisms using GEO and LEO satellites for high-speed vehicles, and iii) converged satellite services with ground infrastructure.

II. Related Work

The introduction of multi-beam satellites coupled with adaptive coding and modulation (ACM) in DVB-S2 [4] based systems allows for a significant increase in capacity [5] for the same RF power and bandwidth. However, multi-beam satellites with conventional payloads provide a uniform capacity distribution per beam, which means that their optimal operating point requires a uniform demand per beam. Flexible satellite payloads with adjustable power and bandwidth per beam or adjustable illumination time per beam (beam hopping) [6] allow the system to overcome this limitation and address the issue of unequal traffic demands [7] across geographic regions. Moreover, both traffic demands and space-time variant channel conditions in ACM based systems must be taken into account in order to provide delay guarantees in joint beam-level and inter-beam resource allocation schemes for flexible payloads [8]. Alternatively, power allocation schemes [8,9,10] or beam-forming techniques [10] allow for multi-beam satellites to implement demand based capacity allocation between beams. All these approaches focus on delivering flexible payloads for next generation satellites without addressing the inefficiencies of existing systems with conventional payloads.

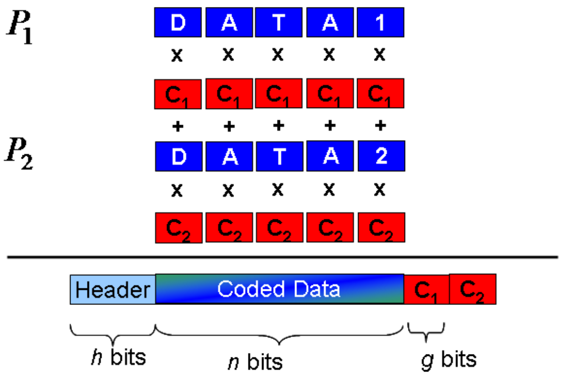

Fig. 1: Example of linear combination of two data packets using network coding. We use symbols in GF(2^g), data packets are of n bits, Ci represents the coefficients of the linear combination. The process ends in a coded packet, composed by coded data, a header and the encoding coefficients.

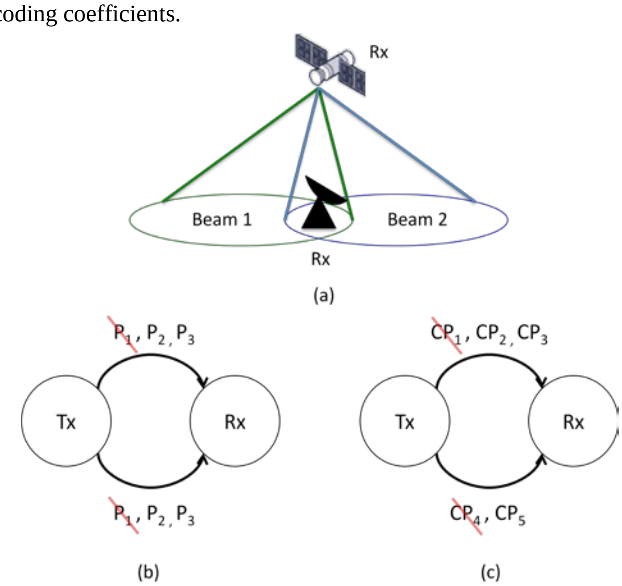

Fig. 2: A simple example of multiple routes in multi-beam satellites. (a) A terminal can receive from both beam 1 and beam 2. (b) Example of a typical soft-handover mechanism transmitting the same 3 data packets through each beam. (c) Example of a network coding approach where coded packets are sent through each beam.

Although handovers are common in terrestrial cellular networks and in mobile satellite communications [11] based on Low Earth Orbit (LEO) constellations, Geostationary Earth Orbit (GEO) multi-beam satellite systems have become relevant in order to provide broadband services to high-speed vehicles such as trains and planes. A common approach is to design algorithms that minimize delay in hard handovers [12], where the terminal switches between two beams without prior resource reservation for receiving data simultaneously from both beams. The path and speed of the vehicle [12, 13] can be used to complement the received signal strength information in order to improve the handover threshold. However, soft-handovers are typically a resource allocation problem, where there is a trade-off between resource reservation for roaming terminals and maximizing the allocated bandwidth for indigenous terminals [14]. Assuming that the terminal can simultaneously receive from both beams, soft-handovers can be further improved by replicating data in both beams during the handover period. These approaches are wasteful in terms of network resources, even when they provide some additional redundancy.

The successful integration of satellite networks into the Internet has been progressing for over 15 years and has lead to implementable standards such as those defined in the IETF TCPSAT [25] and IPDVB [26] as well as DVB-RCS [27] and the ETSI-BSM [28]. More recently the process to ensure seamless interoperability between Broadband Satellite Multimedia (BSM) and Next Generation Network (NGN) and Internet Multimedia System (ISM) has also been standardized in ETSI [29]. While these are major steps towards satellite-terrestrial hybrid networks there remains open challenges in terms of capacity and delay mismatches. And as of yet, satellite-satellite convergence has not being fully investigated. There are many services, from infrastructure support to social television and emergency management, which require revisiting the way satellites and other networks can work together. However the current philosophy still restricts the different transport domains to be clearly isolated [29]. The new challenge is to develop mechanisms to exploit collaboration and interaction across the different domains beyond exchanges of signaling information.

III. Network Coding Fundamentals

The main concept behind network coding is that data throughput and network robustness can be considerably improved by allowing the intermediate nodes in a network to mix (code) different data flows through algebraic combinations of multiple datagrams. In this sense, network coding considers the nodes to have a set of functions that operate upon received or generated data packets. Today's networks would represent a subset of the coded packet networks, in which each node has two main functions: forwarding and replicating a packet. A classical network's task is to transport packets provided by the source nodes unmodified. In contrast, network coding considers information as an algebraic entity, on which one can operate.

From an information-theoretic perspective, it is possible to prove that the multicast capacity of a network is equal to the minimum of the maximum flows between the source and any of the individual destinations [15]. Most importantly, routing alone is in general not sufficient to achieve this fundamental limit — intermediate nodes are required to mix the data units they receive from their neighbors using non-trivial coding operations [1]. It has also been shown that linear codes are sufficient to achieve the multicast capacity [16, 17] and that randomly generated linear codes in a distributed fashion also achieves multicast capacity with high probability [18]. The later is called random linear network coding (RLNC).

Network coding protocols view packets as a collection of symbols from a particular finite field. Nodes in the network forward linear combinations of these symbols across the network, thus leveraging basic features of linear codes such as erasure correction capability and well understood encoding (linear combination) and decoding algorithms (e.g., Gaussian elimination). In RLNC, the coefficients are chosen uniformly at random within the field. The goal of the network is to deliver enough linear combinations (coded packets) to a receiver so that it is able to solve a system of linear equations.

A. Generating a Coded Packet

Figure 1 illustrates the procedure of generating a linear coded packet from two original data packets when considering operations over symbols of g bits, more specifically, operating on a Galois Field GF(2^g). We assume in this example that both packets are of the same length n bits. Two symbols of g bits (C_1, C_2) are chosen to represent the coefficients of the linear combination, also called encoding coefficients. Each packet is split into symbols of g bits. Each symbol of packet P_i is multiplied by symbol C_i and these products are added for the same symbol position of each packet. These generates the symbols of the coded packet, it data content is also of size n bits. Finally, the coded data is concatenated with a header and the coefficients used to generate the data packet, which is needed to recover the information at the receiver.

B. Example of Network Coding with Multiple Routes

We illustrate the idea of network coding in a simple multiple route scenario in Figure 2 and compare it to a more traditional soft-handover technique. Figure 2 (a) represents the case of a terminal that can listen to both beam 1 and beam 2 from a multi-beam satellite. In this sense, the satellite may send information to the terminal through two different routes (beams). A classical system would perform a soft-handover by assigning resources in both beams and sending the same packets through each of the beams, as in Figure 2 (b). This decision is agnostic to the beams' load due to demands from other terminals and is meant to provide additional reliability. In a network coded system, we have the flexibility to send a different fraction of the data through each beam (as long as enough coded packets are sent) and to choose the desired level of redundancy. In Figure 2 (c) the system chooses to send 3 coded packets through one route and 2 through the other due to channel constraints and/or system load.

Although the system of Figure 2 (b) sends one packet more than its coded counterpart of Figure 2 (c), it is simple to see that the coded system provides higher resiliency to packet losses. In our example, both cases may sustain up to two packets being lost. However, without coding when the same packet is lost in both routes, that packet is simply not recovered. Our coded example does not share this problem as different linear combinations can be sent through each route, guaranteeing resilience to exactly 2 packet transmissions, since the receiver only requires 3 independent linear combinations (out of 5 that were generated) to recover the original data.

From the example of Figure 2 (c) it is clear that a coded mechanism can provide additional guarantees of recovering all data packets. However, if more losses occur it may impede the receiver from recovering any single packet. In RLNC, coding across M packets requires M coded packets to recover any information. This is a key challenge to analyze as part of this thesis. The key is to find a trade-off between partial recovery of the data by using a sparser code (RLNC is a dense code) and the inherent loss in performance due to the sparser nature of the code (RLNC is delay-optimal in our example for large enough field). A simple solution is to use a systematic structure, i.e., original packets are sent without coding once, while all additional packets are sent coded with RLNC [19]. Systematic network coding provides no degradation in performance while ensuring i) partial recovery of the packets, and ii) a reduction in decoding complexity, as shown in [19].

C. Challenges of Network Coding

Although network coding provides a series of advantages in terms of throughput, delay, and resiliency there are clearly challenges for wielding these new capabilities. We provide a (non-exhaustive) list of challenges for network coding and strategies to address them.

1. Decoding complexity of RLNC: is that of Gaussian elimination and its code structure may prevent from obtaining partial information if a large number of packets are lost. Recent work in the area has focused on quantifying the trade-offs between structure of the code, partial recovery of the original packets, and performance degradation. For one-hop topologies, a simple mechanism that both reduces the decoding operations and allows for partial recovery of the data is the use of systematic network coding [19], i.e., the system sends the original packets uncoded only sending coded packets for the additional redundancy that is introduced.
2. Where and how much redundancy to add: In general, a higher redundancy should be added for links with high packet loss probabilities. An efficient mechanisms is to generate more coded packets at the node that transmits through a very lossy link, rather than introducing redundancy at the source as it happens in fountain codes. The latter creates an additional burden on the network because it creates end-to-end redundancy. A more interesting question is how much redundancy to add. Work in [20, 21] provides various alternatives for choosing the amount of redundant packets sent depending on the optimization criteria.
3. Feedback or no feedback: although the nature of the content plays a determining role in deciding if retransmission of data packets is possible or not, the question remains of whether to use a FEC approach (no feedback) to the transmission of best effort traffic or to judiciously leverage feedback to enhancing the impact of network coding (e.g., [20]).

IV. Load Balancing in Multi-Beam Satellite Systems

The current design of multi-beam satellites organizes the coverage region into cells, where each cell is serviced by a single beam. Given the dynamic nature of traffic demands at each beam, an opportunity to improve capacity and Quality of Service (QoS) to end users lies in exploiting interactions and coverage overlaps amongst neighboring beams. Our take is that the design of efficient, adaptive multi-beam satellite systems requires knowledge of the overlaps amongst the beams as well as their traffic demands (load) to provide increased throughput through judicious load balancing, namely, identifying how much of each session to send through each beam under certain reliability and (possibly) QoS constraints. The system is highly time-varying due to randomness in traffic demands per terminal and per beam as well as channel variations and terminal mobility.

Although the idea of providing load balancing is rested on a subset of the terminals receiving part of the data from neighboring beams instead of its assigned beam, which leads to inefficiencies in an individual terminal, this is not at odds with providing improved services. The main intuition is that the objective of the system is not to provide the best communication channel per terminal, the objective should be to i) improve the overall system performance, and more importantly ii) guarantee an adequate QoS to the users. Thus, we propose to use idle resources at a beam, because of a low, instantaneous traffic demand, for the benefit of neighboring nodes. A key opportunity is to assign the unused resources judiciously to reduce the individual inefficiency, while reaping the benefits of load balancing.

There exist other load balancing techniques available to flexible payload multi-beam satellites and our goal is not to replace them. Our proposed resource allocation mechanisms are targeted towards managing instantaneous loads, although they can naturally adapt to long-term variations of the traffic demands. Since they operate above the PHY layer, specifically assigning the number of (coded) packets that shall be transmitted through a given beam to the benefit of a specific terminal, and because they also use the SNIR values reported by the terminals to perform the resource allocation, our algorithms can be adapted to coexist with other techniques. This means that it can constitute a complement to other load balancing techniques, such as beam hopping, in order to deal with instantaneous load differences.

Another challenge of designing efficient load balancing techniques is to avoid a domino effect during the process, namely, ensuring that a high load in one or several beams does not compromise the service of the terminals in lightly loaded beams. Judicious algorithms that guarantee service to terminals in lightly loaded beams, while still providing relief to highly loaded beams is then at the top of the day.

Although the underlying assumption has been that load balancing could be performed across all beams, current systems do not provide a single gateway that manages all the beams. In general, there will be multiple gateways managing a subset of the beams. Clearly, load balancing ideas could still apply for subsets of beams (with some performance degradation) but two important questions remain: how can the system coordinate amongst different gateways, and how to reduce the interactions to a minimum if it is computationally or time prohibitive while still reaping benefits as compared to multiple single-gateway allocations.

V. LEO/GEO Satellite Systems

Although we have focused so far on GEO multi-beam satellites, some of the same principles for exploiting multiple routes apply to the problem of soft-handovers in LEO and GEO constellations as well as possible combinations of the two.

Network coding can efficiently exploit multiple non-disjoint routes, which implies that optimality is achieved when not only terminals, but also LEO constellations can communicate with GEO satellites. Under this scenario [23] and given the high predictability of ephemerides, coded packets can be sent through several routes while exploiting: i) the hierarchical network topology of LEO and GEO satellites; ii) the space-time topology inference. While the first improves the coverage of terminals with poor channel conditions to GEO satellites, the latter allows LEO constellations to shift capacity between beams of the GEO satellite by absorbing the resources of lightly loaded beams in order to cooperate in highly loaded beams. With coded packets multiple routes can be exploited without having to guarantee that every packet is correctly received, thus allowing a loose coordination between the GEO satellites and LEO constellations. A second scenario [22] would exclude inter-satellite communications thus eliminating the most of the routes from the previous scenario. Nonetheless, coded packets would still be able exploit the subset of multiple routes available in this scenario, namely at the ground segment, where the satellite networks interconnect.

In both of the previously described scenarios, high speed terminals would be able to exploit the opportunistic communications provided by this dynamic network topology, where network coding would play a vital role in providing the flexibility and robustness in order to provide soft-handovers in this challenging environment. The key role of network coding is to avoid the transmission of repetition of the data packets through each beam or LEO satellite, which is the current state of soft-handovers as seen by the network layer. Instead, we propose the transmission of coded packets and where the system can control the level of redundancy as well as how many coded packets to transmit through each beam or LEO satellite.

Since inter-satellite coordination and dual-receiver terminals for LEO systems are already available in order to provide soft handovers, there is no necessary change in the deployed infrastructure. Given the additional degree of freedom introduced by network coding in terms of having a simple packet encoding function, we can envision soft-handovers that do not only assign fractions of the coded data through different beams (or from different LEO satellite) due to channel conditions. In fact, we can design handover mechanisms that take into account the network's load. For example, if the demand on a LEO satellite is low at a time compared to its neighbors, it can allow a faster transition of a session from another satellite to itself. The rationale is that the lightly loaded satellite can generate and transmit additional coded packets to compensate for poor channel conditions.

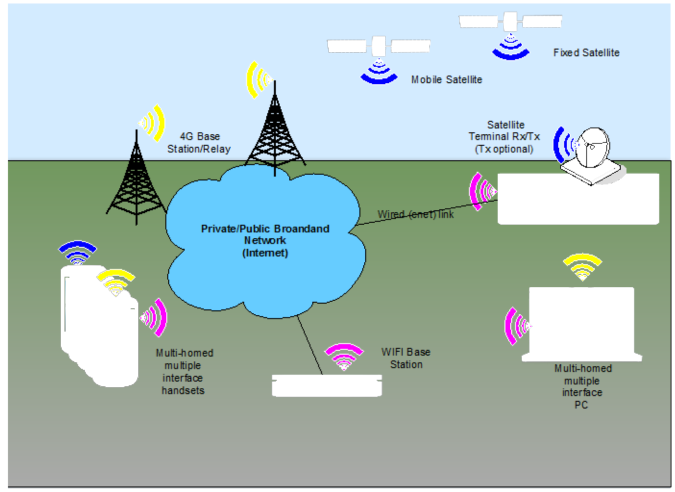

Fig. 3: Converged satellite ecosystem

VI. Convergence

The development of new mobile broadband networks, such as terrestrial 4G networks, include some key characteristics that clearly go beyond current systems: very high spectral efficiency, dynamic resource allocation for increased number of users per cell, all-IP core and smooth handovers across heterogeneous networks (Fig. 3). While a multi-beam satellite system based on DVB-S2 can fulfill most of these requirements, convergence with other satellite and terrestrial technologies and smooth handovers between networks requires an approach such as network coding. Furthermore, it even provides increased efficiency in terms of resource allocation, while exploiting the native IP core.

Although convergence between satellite systems has been considered before (e.g., [24]) these systems become very complex. Network coding provides the means to seamlessly transmit and gather the required information without focusing on the correct reception of individual packets.

VII. Conclusions

This paper discusses network coding as an enabler to be used in current and future satellite systems for enhancing resource allocation mechanisms and quality of service to the end users. Satellite networks are not just a natural environment for providing broadcast and multicast services, but can also provide multiple, heterogeneous routes from sources to end users, which provides more flexibility for system operation. We studied three main cases of interest. First, we analyzed load balancing mechanisms for multi-beam satellites based on network coding. The multiple routes are available through overlapping beams and ground terminals that are able to receive and process the signal from each beam. Network coded packets can be generated and managed at the encapsulation level and/or network layer of the satellite stack. Although our findings are useful for conventional payload systems, we can exploit similar procedures in beam-hopping satellites. Our techniques are thus complementary to beam-hopping satellites providing adaptability to short term traffic dynamics. Second, LEO/GEO satellite systems were analyzed as more complex topologies, where network coding could reduce coordination efforts for the transmission of information. In particular, we emphasized their use for providing enhanced soft-handover mechanisms. Third, we envision disruptive converged satellite architectures aimed at providing a higher quality of experience to the user for content-delivery.

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