Challenges for Efficient and Seamless Space-Terrestrial Heterogeneous Networks[1]

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Abstract

By interconnecting satellites in the sky with ground stations on the earth, space-terrestrial networks can extend the coverage area and increase the throughput for both commercial and non-profit applications. To realize the seamless and economic sky-to-earth networks, we still have to advance the technologies that bridge different types of channels, and find killer-applications that are essential for our life. In this article, we review the current state-of-the-art technologies of multibeam satellites and relaying as fundamental cornerstones, and then address the issues for low-latency random access, mobility support, and multipath protocols for realizing a seamless heterogeneous network. We then illustrate two impactful applications: for emergency communication as a near-future and non-profit application, and for simultaneous transmission of information and power as a long-term application.

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1. Introduction

The capability of satellites can be enhanced when they are interlinked with ground components, which can fill some coverage holes and improve system throughput. The non-line-of-sight (NLOS) environments inside buildings or undergrounds where satellite signals are not easily received can be covered by relaying temporarily built WiFi/Bluetooth or partially working 3G/LTE signals to satellite networks. When the network architecture interconnects the different components over the sky and on the ground with the system heterogeneity into account, the performance of space-terrestrial “heterogeneous” networks can be significantly enhanced, especially for disaster recovery and rescue coordination. In addition to the traditional application for information transmission, the simultaneous transmission of information and power from satellites can allow uninterrupted connectivity to isolated areas. The space-based solar power transmission from satellites has been a long-term project and is finally planned to be realized in a few decades [1]. Space-terrestrial heterogeneous networks can feed solar power from the space to large rectennas (rectifying antennas) located in unpopulated areas, and then distribute to each user through terrestrial power line or wireless links.

In this article, we investigate the enabling technologies for multi-purpose space-terrestrial networks that achieve both high spectrum efficiency and low latency. We explore the technical challenges in interconnecting satellites with terrestrial networks such as LTE and WLAN. In particular, the main thrusts to enhance the economics of the space-terrestrial network are as follow:

• Multibeam satellites that generate agile narrow spotbeams by controlling interbeam interference.

• Relaying architecture that interconnects multibeam satellites and ground stations for the multi-dimensional performance objectives of throughput, delay, power consumption, and reliability.

• Low-latency random access that overcomes long propagation delay with distributed resource allocation schemes in satellite uplink.

• Mobility support at high frequency bands that enhances the economics of satellite communications despite delayed channel state information (CSI).

• Multipath protocols that are optimized in cross layers for quality of service (QoS) guarantees across space and terrestrial network components.

We then discuss a few examples where the space-terrestrial networks can be applied as killer applications in a near and long term, respectively:

• Emergency communications that are essential for disaster recovery and rescue missions by connecting non-satellite users through (partially working or temporarily deployed) terrestrial networks.

• Simultaneous transmission of information and power that can distribute solar energy from multibeam satellites to the Earth, as illustrated in Fig. 1 for a scheme of emergency networks.

In the rest of this article, we focus on the current status and future outlook of the technologies and applications listed above, which range from the ones being actively studied or currently being implemented (e.g., multibeam satellites, relaying architecture, and emergency communications), to the others being considered for a possible use in the future but still to be proved beneficial. To fill the gap between practical importance and future interests of our selection, many ongoing research activities will be presented as well, including interference mitigation techniques, multi-input-multi-output (MIMO) systems, network coding, delay diversity techniques, and advanced diversity/handover concepts for mobility support.”

2. Enabling Technologies

A. Multibeam satellites

Multibeam satellites are currently a state-of-the-art technology for commercial satellite networks such as Inmarsat and Globalstar. Narrow spotbeams can project high power density and thus can support high data rates to small user terminals. In addition, an identical frequency spectrum can be reused in multiple distant cells, increasing the total system capacity. Advanced multibeam satellite equipped with phased array antenna can effectively serve a large number of users over its coverage area by beamforming narrow spotbeams and managing interbeam interference. It is shown in Fig. 2(a) that phased array antenna techniques such as agile antenna gain patterning and beam scheduling can achieve 74% of the maximum capacity while serving interfering users located within 1/4 of mainlobe beamwidth from each other [2].

The core Physical-layer components that realize multibeam satellites are active array antenna and solid-state power amplifiers (SSPA). The phased array antenna (Fig. 2(b)) can adjust the size and/or shape of beam by feeding many array elements from SSPA, and linearly superimpose signals by controlling an antenna-patterning matrix. Moreover, the phased array antenna together with transmission scheduling switches faster than 1 msec, which is desirable for delay-constrained transmission. Flexible antenna gain patterning allows for simultaneous service of users in a populated area by suppressing possibly significant interbeam interference. The impact of interference can be addressed by a new class of high layer protocols. Note that the static beamforming with traveling wave tube amplifiers (TWTAs), which require a high power margin and have been widely used in satellite communications traditionally, achieves only a fraction of the throughput achieved by SSPA and phased array antenna in Fig. 2(a). It is still a challenging research topic to design high-efficiency gallium nitrate (GaN) SSPA in a large scale. Interference mitigation using beamforming techniques [3] and exploiting dual satellites or polarization for MIMO communications [4] are being adopted to improve the efficiency of multibeam schemes.

B. Relaying

Relaying is one of the key elements of 4G/5G cellular systems as it can extend the coverage outside the cell-edge and take traffic load off from the macro base stations. The seamless relaying through heterogeneous radio access technologies has yet to be realized in practice due to difficulty of controlling different protocols though different channels. The benefits and difficulties of realizing relay networks are equally applied to the space-terrestrial network. The overall system throughput of multibeam satellites can be enhanced when ground stations such as gateways, gap fillers or feeder antennas are also utilized for path diversity. If packets have to be retransmitted, the ground stations can fulfill the request, getting rid of long propagation delays from satellites.

The frequency bands of satellite-to-earth and terrestrial links may overlap entirely or partially, in which case the allocation of the shared spectrum should be coordinated not to degrade the entire system performance. As the cellular communication technology advances rapidly and the demand for spectrum increases unexpectedly, the standard community has been paying more attention to spectrum sharing (for example, around 2.1 GHz) between satellites and terrestrial cellular networks. Since onboard resource management has been only analyzed without terrestrial resources into account so far, resource allocation of the space and ground components should be jointly coordinated. By incorporating ground stations to receive satellite signals, the multibeam satellite has a choice of routing signals to gateways/feeder antennas and/or sending directly to end user terminals. A cross-layer approach takes into joint account the PHY layer rate/power allocation, the MAC layer user scheduling, the Network layer routing path selection and Transport layer congestion control. The scheduling scheme seeks for a trade-off between the use of satellite and terrestrial resources, and compensates for the weakest link in the space-terrestrial heterogeneous network. For the heterogeneous network to guarantee seamless service in practice, more robust integration of heterogeneous channels should be realized yet: for example, hybrid automatic repeat request (HARQ) packet retransmission based on punctured codes in the terrestrial link.

C. Low-latency random access

In the satellite coverage area, many users compete for uplink access to the satellite transponder. In the random access such as the Aloha protocol, users rely on randomness of their signal transmissions in a distributed manner, achieving low latency because data can be transmitted without waiting for the resource allocation from the central coordinator. On the other hand, in heavily crowded communication systems, collisions from random access can cause severe throughput degradation and additional delay. A potential solution would be the use of carrier-sensing functionality as in the terrestrial networks, called as carrier sense multiple access (CSMA). Under CSMA, each user monitors the status of the channel before its signal transmission, and starts transmission only when the channel is unused. A hybrid approach that combines the reservation scheme is also possible. For example, on recognition of an idle channel, a user can send a short packet ahead of real data and reserve longer slots for the data, obtaining higher throughput without excessive waste of resource due to collision.

A critical weakness of CSMA approach in the satellite network is again the excessively long delay for signal propagation. When a user senses an idle channel, the information is already stale and its signal transmission may collide with others when it eventually arrives at the satellite antenna, leading to a failed attempt for reservation. One way that tackles the issue is to develop random access schemes based on each user's understanding of the impact of its transmission on the others instead of making reservations. For example, each user measures the signal to interference ratio (SIR) over downlink channels, infers the uplink SIR under the assumption of channel reciprocity, and dynamically adjusts its random access time, backoff parameters, and transmission power. Since many users on the Earth will access to a much smaller number of satellites in a distributed manner, more rigorous coordination of random transmissions and power control for the system stability is necessary, imposing additional control overhead and latency for information exchange. Otherwise, as in the heavy load scenarios of Aloha networks, multiple transmissions will severely interfere with each other and a significant amount of resources will be lost. It is worth noting that a joint design of admission control and random access could be beneficial to guarantee QoS and fairness among users.

D. Mobility support at high frequency bands

For cross-layer optimization of the satellite network it is critical to input the accurate PHY information, such as channel state information and geographical user locations, into high layers and to adapt high-layer protocols according to time-varying satellite channel conditions and user mobility. In an example of successful mobility management the location information update is decoupled with handovers that can be frequent for non-geostationary satellites, thus reducing the amount of information uploaded to the satellite [5].

As for channel state information, channel modeling for high frequency band communication satellites has been, so far, mainly focused on weather impairments, such as rain attenuation and atmospheric scintillation. The coherence time of weather-induced channel variation is in the order of seconds and longer, and does not cause severe performance degradation to prediction of the channel states and the corresponding system adaptation. On the other hand, channel variation due to multipath and mobility is much faster than the round-trip delay. It is known that the capacity of the time-varying channels can increase only if the channel feedback delay is within the channel correlation time [6]. The performance of satellite-terrestrial heterogeneous networks at higher frequencies can be enhanced by adding mobility support and system adaptability to fast time-varying channels, for which the current practical system design does not fully make up.

It is still an open problem how to overcome the difficulty of predicting fast time-varying channels, and to develop a new class of protocols for adapting systems accordingly. Not only the technical challenges, but low demands for deploying satellite networks in the urban and/or high-speed environments have been obstacles. Another bottleneck is the speed and accuracy of the current beam switching technology. Unless the advanced phased array antenna is used, provisioning agile spotbeams to mobile users in the urban channel condition is not a simple task even if the perfect channel state information is known to satellites. Thus, instead of the channel prediction and adaptation as for weather-induced channels, it has been suggested to provide an option of more redundancies, so that users in fast time-varying channels can take advantage of them in case of poor channel conditions, but do not have to do so otherwise.

Retransmissions via ground stations or advanced coding schemes such as multi-layer coding [7] can improve the supportability of mobile users and mitigate the blocking/multipath effects in the form of retransmitted packets and the longer coded packet length. The network coding technique can be combined with ARQ protocols to reduce delay further and increase throughput [8]. The new protocols in the MAC layer will incur the proper modification in other layer protocols that have been optimized only for slowly time-varying weather-induced channels. For example, by considering potential retransmissions, more packets are forwarded to ground stations than when redundancies are not taken into account. At the same time, since the delay-sensitive packets should be headed to users directly, multi-path routing and the corresponding multi-path Transport layer protocol should be deployed for network performance optimization. Diversity and co-operation using terrestrial stations are the promising solution for adding mobility support to high-frequency satellite networks despite incurring redundancies and coordination/synchronization between satellites and Earth stations. If the co-operation with terrestrial stations is enough to support user mobility on the fast time-varying channels, the system performance degradation due to the imperfect CSI of the fast time-varying channel can be alleviated since the measurements and modeling of the satellite channels at high frequencies are extremely time-consuming. Table 1 summarizes the current technologies and future trends for fixed and mobile user support in LOS and NLOS environments, respectively.

E. Multipath protocols

Multipath protocols are to support diversity/co-operation and low-delay transmission in the space-terrestrial heterogeneous network that operates different types of protocols over multiple signal paths with different channel characteristics. The current MP-TCP (Multipath Transport Control Protocol) has been developed to support parallel TCP subflows and shows a drastic change in performance based on multipath characteristics. Compatibility with legacy single-path TCP is one of the key issues in the community. To prevent starvation of legacy TCP, MP-TCP connection is supposed to not overwhelm a legacy TCP in each path, while its overall performance is better than a single-path TCP in the best-quality path [9]. To exploit multi-path diversity while providing the backward compatibility, it is imperative to couple transmission window sizes between subflows. The problem becomes more challenging when multiple paths have significantly different characteristics. In particular, if one of the subflow is through Long-Fat Networks (LFN) such as satellite networks, detecting changes in system dynamics takes more time, which often leads to waste of scare wireless resources and degradation of throughput performance.

Guaranteeing delay performance becomes harder due to complicated interplays between the sender, intermediate routers, and the receiver. Since a single flow is split into multiple subflows, its packets not only experience different network delays, but also have to wait for previous packets at the reordering buffer of the receiver as shown in Fig. 3(a). Recently, by controlling packet transmission times based on queuing delays, channel conditions, and propagation delay, it has been shown that a modified version of MP-TCP can reduce the end-to-end delay at a reasonable user cost as shown in Fig. 3(b) [10]. The development of multipath protocol should be focused on both frontiers of extending the existing protocols to the multipath environment and developing a new class of protocols optimized for heterogeneous types of channels. Since the space-terrestrial network has extremely distinct characteristics for each signal path, we first have to analyze the asymmetry of multipath in terms of channel fading, propagation delay, and available bandwidth. The optimal control of up/downlink traffic should be able to compensate for the path heterogeneity and consider transmitter/receiver buffer occupancies as well. However, since the multipath control may impose additional complexity on already-sophisticated resource management or result in unnecessary packet transmissions, a careful tradeoff study between performance and complexity is required.

3. Applications

A. Emergency communications

One applicable scenario to use a space-terrestrial network for emergency communications is when a disaster recovery team is deployed for rescue coordination and relief efforts in the area where terrestrial infrastructure is heavily damaged. The recovery team sets up mountable antennas that can play a role of gateways or relay stations between the satellite and end user terminals. The satellite plays a role of a core network while the temporarily deployed or partially working terrestrial links relay satellite signals to surrounding areas including NLOS environments. Each end user terminal for a recovery team member can also receive the satellite signal directly from the satellite if the terminal supports the dual mode at the same time. User mobility support and low-latency random access will be indispensable for receiving direct satellite signals and sending direct requests to the satellite if the member's mission is time-sensitive or the mission area is too wide to be covered by gateway stations.

Co-operation between space and terrestrial networks has attracted much attention as a promising technology for emergency communications. For example, the WISECOM (Wireless Infrastructure over Satellite for Emergency Communications) project in Europe uses Inmarsat and DVB-RCS (Digital Video Broadcast - Return Channel via Satellite) to backhaul terrestrial traffic from 3G/4G, WiFi, TETRA (Terrestrial Trunked Radio), etc [11]. A simple amplify and forward scheme with diverse delay paths can be shown to improve bit error rate (BER) performance by introducing additional frequency selectivity in the NLOS channel [12].

The path diversity of the multibeam satellite can be exploited to improve reliability in emergency communications. However, the multipath-support protocols such as network coding and MP-TCP face challenging problems of choosing a better signal path, optimizing coding block size, considering transmission diversity for higher reliability, and segmenting a packet for better throughput. If multimedia packets can be received from other members or headquarters with guaranteed QoS levels, a rescue member can carry out missions more efficiently and understand potential dangers more easily. Since the terrestrial ad-hoc network can be used for direct communications among rescue members, the satellite signals should be scheduled not to interfere with (and also not to be interfered by) the terrestrial signals if they operate in the same or adjacent bands. The problem of user scheduling and resource allocation for emergency communications can be formulated to give answers to other questions, such as the location and the number of ground gateways, the single or dual mode of receiver terminals, etc. Since it is critical to minimize power consumption and save battery power in the disaster where power distribution infrastructure does not function in the full capability, the power consumption of satellites and ground stations should be the major consideration for the CAPEX (capital expenditure) and OPEX (operation expenses) of the emergency network.

B. Simultaneous transmission of information and power

The wireless power transfer technology has recently drawn attention of communications and energy experts since it can alleviate the power shortage problem of communication nodes and devices. However, the state-of-the-art practical application is limited to a very short range transfer (less than 1m) only using resonant inductive coupling, and ongoing research for solar power transmission has primarily focused on the mechanical and physical technologies, such as very wide solar panels, satellite body structure, and a large scale of rectennas [13]. On the other hand, simultaneous wireless information and power transfer (SWIPT) [14] is also under active research in academia since it can ensure the timely delivery of information under harsh environments. For example, in disaster scenarios, power stations can be also damaged and the rescue effort can be restrictive due to unreliable communications. Since a short halt of communications can be critical for the mission, simultaneous transmission of power and information in the space-terrestrial network will be extremely beneficial as illustrated in Fig. 1. Although the wireless power transfer technology is not close at hand in practice, the development of the high-layer architecture and protocols for simultaneous transmission of information and power should be accompanied to advance the realization of crucial applications such as emergency networks.

When power transmission from satellites is mathematically modeled and practically implemented, we have to compare common and different features between information and power transfer. Signal attenuation due to free-space loss is governed by the Friis transmission equation in the same way as for information. The power transmitted from the Ka band GEO satellite is attenuated by more than 200 dB by free-space loss only. Assuming the rectenna receiver gain up to 130 dB with a wide diameter of 3 km, the beamforming gain of near 80 dB at the transmitter with a diameter of the order of 10~100m would be preferred. Since the rectennas for solar power are currently planned to be located in unpopulated areas such as deserts and oceans due to safety reasons, multipath effects are not considered to be a major concern. Rain and moisture at the atmosphere are still big causes for power attenuation, making it hard to utilize high frequency bands. Channel prediction and system adaptation techniques should be more aggressive for power transmission. Nevertheless, a simple method of shutting down power transmission to an area with a bad channel condition can still improve the transmission efficiency. The trade-off between power and information transfer in terms of bandwidth allocation, which is shown in the short-range resonant coupling [15], is also applied to the long-range transmission. The wider the bandwidth is, the bigger the information capacity is, but the less efficient the power transfer is. High-efficiency wideband antennas for power transmission and reception can be made of GaN solid-state power amplifiers, which is one of the major research areas for solar power transmission. Table 2 compares the differences between information and power transmission.

A multibeam-satellite resource allocation problem for simultaneous transfer of information and power to the terrestrial relaying network should be set up for the maximum power transfer under the constraint of guaranteeing the minimum information transmission. Power transmission spotbeams should have maximum power constraints, which are not imposed for information transmission beam unless TWTAs are used. Due to health safety and environmental protection, the amount of received power should be controlled under an allowable threshold. By extending the result on relaying information transmission via ground stations, the optimal solution for power transmission should be also based on channel conditions, user demand for power and information, QoS requirements, and interference among spotbeams themselves and with terrestrial radios. For the feedback of such information from/to ground stations, low-latency random access and multipath protocols will play the key role for the information delivery in a timely and reliable manner. Further, for unmanned devices and robots that conduct critical mission in harsh environments, the mobility support will be crucial in simultaneous transmission of information and power.

The formulation and modeling can be an initial step towards realizing solar power transmission to the Earth in the near future. Following more detailed performance analysis of satellite resource allocation, we will need to design efficient control and feedback signals from ground to satellite, ultimately interconnecting solar power satellites and terrestrial smart grids for direct power reception of mobile end users.

4. Conclusion

Starting from the basic building blocks of multibeam satellites and relaying technology for space-terrestrial heterogeneous networks, this article addressed technical challenges of developing advanced technologies of low-latency random access, mobility support over fast time-varying channels, and multipath protocols. High-impact applications of emergency communications and simultaneous information/power transmissions can benefit from each technology, as summarized in Table 3. We believe that the space-terrestrial network will broadly impact on different industry sectors of commercial Internet, remote sensing/monitoring, disaster response, green energy distribution, etc., and be of invaluable significance for geopolitics, diplomacy, and military defense.

References

[1] S. Sasaki, “It's always sunny in space,” *IEEE Spectrum*, pp. 38-43, May 2014.

[2] J. P. Choi and V. Chan, “Resource Management for Advanced Transmission Antenna Satellites,” *IEEE Trans. on Wireless Communications*, vol. 8, No. 3, pp. 1308-1321, March 2009.

[3] G. Zheng, S. Chatzinotas, and B. Ottersten, "Generic Optimization of Linear Precoding in Multibeam Satellite Systems," *IEEE Trans. on Wireless Communications*, vol. 11, no. 6, pp. 2308-2320, June 2012.

[4] P. Arapoglou, K. Liolis, M. Bertinelli, A. Panagopoulos, P. Cottis, and R. De Gaudenzi, “MIMO over Satellite: A Review,” *IEEE Communications Surveys & Tutorials*, vol. 13, no. 1, pp. 27-51, First Quarter 2011.

[5] H. Tsunoda, K. Ohta, N. Kato, Y. Nemoto, “Supporting IP/LEO satellite networks by handover-independent IP mobility management,” *IEEE Journal on Selected Areas in Communications*, vol. 22, no.2, pp.300-307, Feb. 2004.

[6] H. Viswanathan, “Capacity of Markov channels with receiver CSI and delayed feedback,” *IEEE Trans. on Information Theory*, vol.45, no.2, pp.761-771, Mar 1999.
[7] J. Arnau, A. Rico-Alvarino, and C. Mosquera, Adaptive Transmission Techniques for Mobile Satellite Links, *30th AIAA International Communications Satellite Systems Conference (ICSSC)*, 2012.
[8] S. Sorour and S. Valaee, “A Network Coded ARQ Protocol for Broadcast Streaming over Hybrid Satellite Systems,” *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2009.
[9] A. Ford, C. Raiciu, M. Handley, S. Barre, and J. Iyengar, “Architectural Guidelines for Multipath TCP Development,” IETF RFC 6182, March 2011.
[10] S.-Y. Park, C. Joo, Y. Park, and S. Bahk, “Impact of Traffic Splitting on the Delay Performance of MPTCP,” *2014 IEEE International Conference on Communications (ICC)*, June 2014.
[11] M. Berioli, A. Molinaro, S. Morosi and S. Scalise, “Aerospace Communications for Emergency Applications,” *Proceedings of the IEEE*, vol. 99, no. 11, pp. 1922-1938, Nov. 2011.
[12] S. Morosi, S. Jayousi and E. Del Re, “Cooperative Delay Diversity in Hybrid Satellite/Terrestrial DVB-SH System,” *IEEE International Conference on Communications (ICC)*, May 2010.
[13] S. Sasaki, K. Tanaka, and K. Maki, “Microwave Power Transmission Technologies for Solar Power Satellites,” *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1438-1447, June 2013.
[14] K. Huang and V. K. N. Lau, “Enabling Wireless Power Transfer in Cellular Networks: Architecture, Modeling and Deployment,” *IEEE Trans. on Wireless Communications*, pp. 902-912, Feb. 2014.
[15] P. Grover and A. Sahai, “Shannon meets Tesla: wireless information and power transfer,” *2010 IEEE International Symposium on Information Theory Proceedings (ISIT)*, pp. 2363–2367, June 2010.

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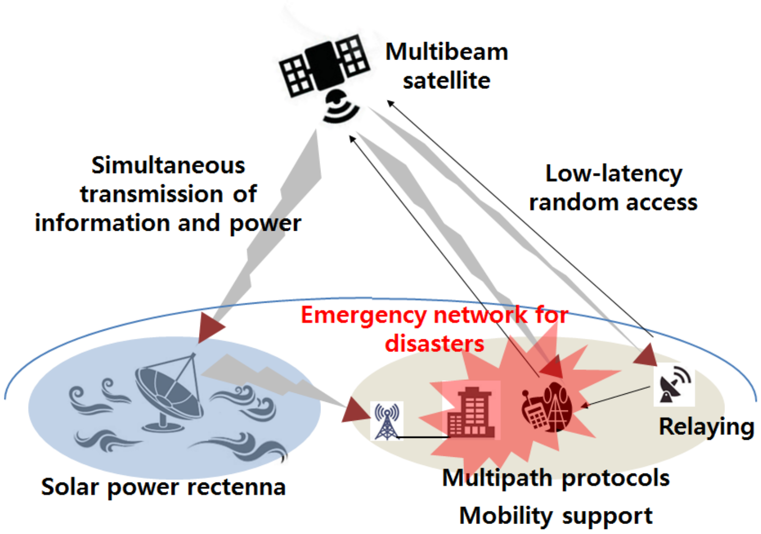
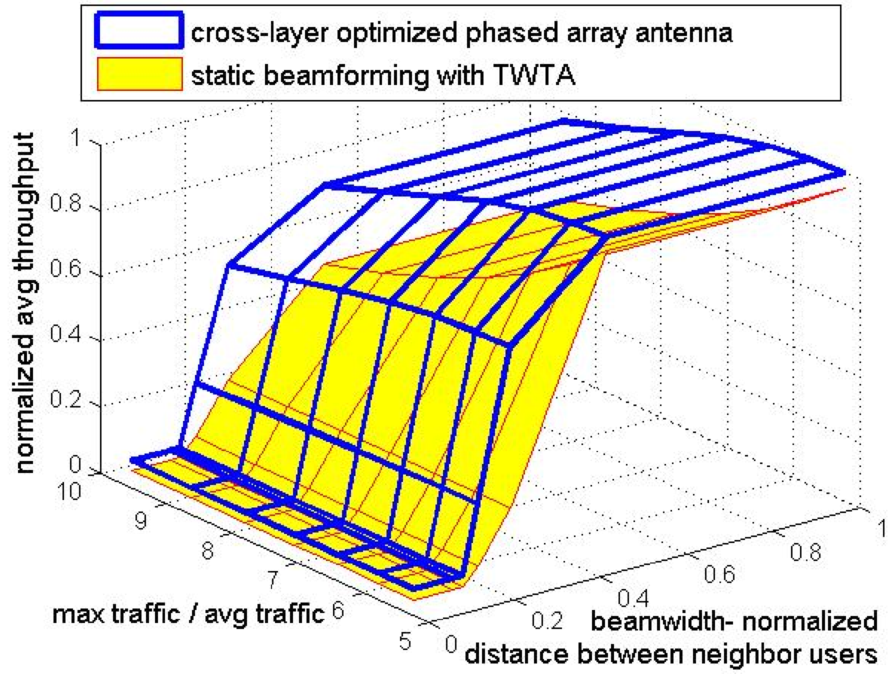


Fig. 1. Scheme of emergency networks with simultaneous transmission of information and power.



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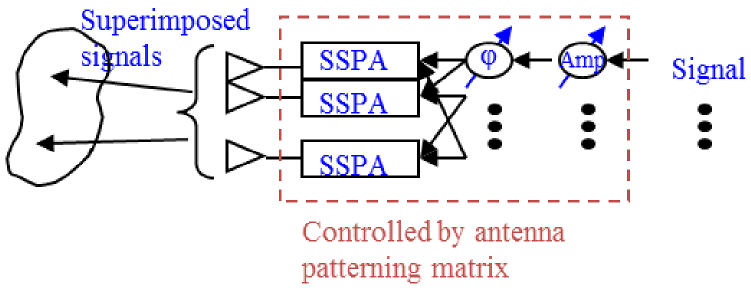
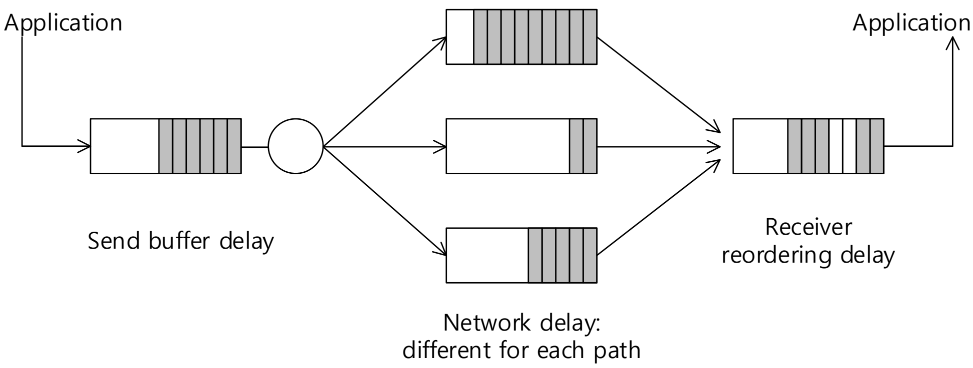


(b)

Fig. 2. (a) Performance and (b) diagram of phased array antenna (adopted from [2]).

		LOS (line-of-sight) environments	NLOS (non-line-of-sight) environments
Fixed users	Channel characteristics	Slow time-varying (channel coherence time > 1 second)	
		Channel modeling of weather-induced impairments using log-normal and Rician distribution	Not a major interest (If necessary, bad channels in the Markov channel modeling)
	Communication strategies	Channel prediction and system adaptation	
Mobile users	Channel characteristics	Fast time-varying (channel coherence time < 1 millisecond)	
		Channel variation mainly due to Doppler effects	Most vulnerable channels due to multipath, shadowing, blocking, and Doppler effects
	Communication strategies	Path diversity and co-operation, such as HARQ and multi-layer coding, using terrestrial networks	

Table 1. Fixed and mobile user support comparison for LOS and NLOS environments.



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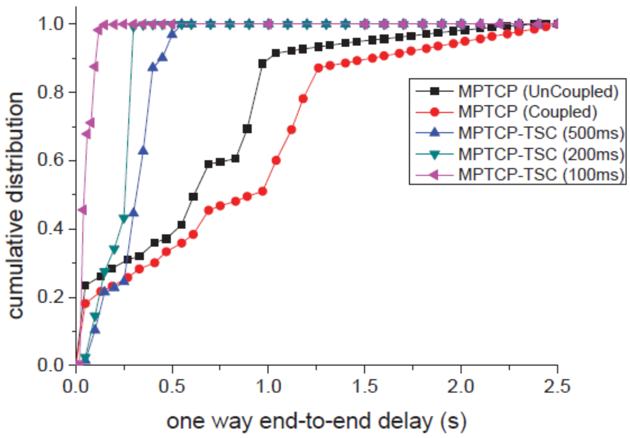

(b)

Fig. 3. (a) Latency model of MP-TCP and (b) comparison of MP-TCP schemes (adopted from [10]).

	Information transmission	Power transmission
Free space loss	Proportional to the squared distance	
Transmitted power level	~ 1kW	Up to 1GW
Satellite antenna size	< 10 m	~ 100 m
Ground station antenna size	~ 10 m	~ 3 km
Mobility support	Yes	No
Power attenuation	Rain, atmospheric moistures, multipath, shadowing, blocking, Doppler shifts	Rain and atmospheric moistures
Power amplifiers	TWTA, SSPA	Klystron, magnetron, SSPA (made of GaN)

Table 2. Comparison of information and power transmission.

	Emergency communications	Simultaneous Tx of information and power
Multibeam satellites	Diversity and increased throughput	Simultaneous delivery with diversity
Relaying	Coverage extension and reliability	Feasible location for rectennas
Low-latency random access	Time-sensitive responses and feedback	Interactive communications for smart distribution
Mobility support at high freq.	Direct reception for time-sensitive packets	Direct power reception of mobile end users
Multipath protocols	Reliable delivery of timely information	Efficient resource allocation using alternative paths

Table 3. Use of technologies for applications in the space-terrestrial heterogeneous network.