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The Small Satellite Integrated Communication Environment (I.C.E.) – An Update

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ABSTRACT

The Integrated Communication Environment (ICE) concept was initially presented at the 2014 Small Satellite Conference. This paper presents the results of an analysis we subsequently performed that establishes the viability of this novel satellite communication technology. Our point to point link budget analysis confirms that a viable ICE system can be realized using 4G LTE technology operating at 1.9 Gigahertz that can yield a data rate of more than 3 Megabytes per second. Continuing advancements in cellular technology, increases in bandwidth, and low installation costs offer the small satellite community a global satellite communication solution that has significant advantages over legacy ground site system architectures. The ICE approach effectively offers a simple means to upload your satellite command plans via email or text while downloading streaming live data through a select set of modified cell towers. Additionally, and even more importantly, it offers a new layer of Space Resiliency by migrating communications from highly vulnerable ground sites to thousands of cellular nodes.

A key component of the ICE concept is to modify existing cellular towers by adding fixed upward-pointing, narrow beam antennas. A single cell tower provides only limited communications access. However, by distributing these antennas over appropriately spaced cell towers we can create overlapping coverage that spans very large areas. The goal is to integrate satellite communications into existing cellular networks to break free from the legacy ground station approach, thus offering a new communications paradigm for future satellite programs. The satellites themselves must also be modified, but SMALLSAT and NANOSAT satellite systems already exploit the size, sophistication, and capabilities of Smartphone technology, which is currently being considered for the operating system on many new small satellite applications. The benefit of using this technology is further enhanced when one considers the inherent communications capabilities offered by these highly sophisticated devices. Although the technology has greatly evolved over the past decade for terrestrial use, modifications will be required for the satellite communications application; such as increased transmit power in conjunction with a downward pointing high-gain antenna. In the ICE concept, a generic approach is proposed for sending data to and from the satellite in logically-small transfer packages (ICE Pacs), designed to identify standardized data types: Command and Control (C2) uplink; Status of Health (SoH) downlink; Data Packages; etc.

ICE not only offers a novel and affordable means for communicating with small satellites, but can stimulate growth of a whole new community that supports this communication concept solution. At the national level, ICE offers the Space Resiliency community a low cost risk mitigation layer in the event that communications with legacy ground sites is lost. As we begin to launch large constellations of small satellites, it is becoming increasingly clear that the legacy ground site architecture will not meet the communications demands needed to realize the benefits of these small satellite constellations. It is time to put our legacy satellite communications approach on ICE.

PROBLEM STATEMENT

With the proliferation of SMALLSAT and NANOSAT satellites, the usual method of communicating with satellite systems using dedicated ground stations with dish antennas is rendered ineffective. This method provides only limited daily access, requires dish operation, and is limited to a single satellite at a time. Satellite constellations will be competing for valuable access time to downlink their data. As these demands for increase, so will the cost.

SOLUTION

The solution is simple: modify existing cellular towers to provide a fixed upward pointing narrow beam antenna. A single cell tower provides limited communication access, but distributing these antennas over appropriately spaced cell towers provides overlapping coverage spanning large areas of arbitrary size (Figure 1).

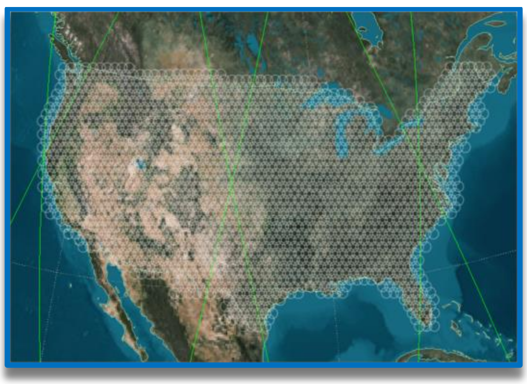

Figure 1: Overlapping Coverage Illustration

The goal is to integrate satellite communications into the existing cellular networks to break free from the legacy ground station concept by offering a new Integrated Communication Environment (ICE) for all future satellite programs. Leveraging years of communication experience, technology miniaturization, signal processing, and an extensively populated ground infrastructure make this an attractive and affordable communications solution for future satellite systems.

ICE COMPONENTS

The following description of the ICE components is repeated from the 2014 SMALLSAT Conference paper SSC14-IX-8 [1], and is provided for completeness.

Satellite ICE Module

Many of today's SMALLSAT and NANOSAT satellite systems employ smartphone technology for onboard data processing based on considerations of size, sophistication, and needed capabilities. ICE leverages the communications capability of these powerful devices to transmit and receive data to and from the satellite. As ICE communication technology advances the need to wait for hours to access the next available ground site will become history.

Smartphone technology is currently being considered for the operating system on many of these new small satellite applications (Figure 2).

Figure 2 – DROID™ Integration into Satellite Technology

Although this technology has greatly evolved over the past decade for terrestrial use, some modifications are required for a satellite communication implementation. A link budget analysis was conducted and results are presented below. Since the typical human operational safety issues in the cell phone implementation do not apply, increases to transmitter power and high gain antennas are viable considerations for ensuring a successful link budget.

ICE Cell Tower

Current cellular towers are dedicated to providing the necessary coverage for terrestrial communication through antennas aimed at the horizon. ICE requires that a directional upward pointing antenna be integrated on existing cell towers (Figure 3).

Figure 3: Zenith Antenna Integration

Based on the particular cellular network and available transmit/receive frequencies an antenna configuration can be designed to provide the required orbital footprint at Low Earth Orbit (LEO). For this analysis, we assumed a 300 km altitude orbit. An LTE network operating at 1.9 GHz requires a 50 cm diameter dish (slightly larger to minimize interference with terrestrial antennas) to create a 22 degree footprint in space. This footprint requires an ICE cell tower antenna every 60 miles to provide pattern overlap. The details of the design will vary depending on the selected network and available frequencies.

Key to the ICE concept is a network of many cell towers, appropriately spaced, to provide overlapping orbital coverage at LEO satellite altitudes. Based on the known satellite flight path, a string of cell towers can be activated to offer continuous contact for sending large data files to the ground.

The Virtual Ground Site

The ICE approach relieves the satellite community dependence on traditional dedicated ground sites, and instead establishes a virtual satellite monitoring system. A generic approach will be used to send data to and from the satellite in logically-small transfer packages (ICE Pacs). Based on cell tower access statistics (15 seconds of comms per tower), packages will be designed to identify standardized data types as Command and Control (C2) uplink; Status of Health (SoH) downlink; and Data Packages (puzzle pieces in Figure 4).

Software will be designed to monitor SoH, manage customer needs, perform satellite sensor tasking, create satellite commands and manage satellite operations, operate the ICE Network (under certain operational demands such as Multiple-Cell Tower Operations), and manage the ICE Pacs into logical ICE Trays (Figure 4).

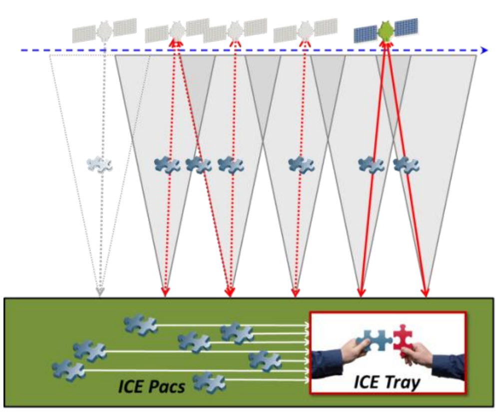

Figure 4: The Virtual Ground Site

Although existing telecommunications infrastructure will be used to seamlessly integrate the ICE network, there are refinements that can be made to minimize typical cellular communications operational overhead. For example, the fact that the satellite trajectory is known allows us to configure the appropriate sequential cell towers to act as one continuous connection and offers the potential for seamless video transmission.

TECHNICAL CONSIDERATIONS

Although the ICE concept leverages the success and maturity of existing cellular network technology, integration of these pieces into the ICE system presents several technical hurdles: cell phone communication hardware onboard satellites, satellite antenna and transmitter power requirements, cell tower antenna and associated transmit/receive hardware, selecting the appropriate cellular phone network, software to manage the system, etc. The goal is to make communications achievable and affordable by simply incorporating the necessary cellular equipment into the satellites. Despite the many technical issues that must be resolved, the most difficult challenge is likely to be political: “How do we convince industry to invest in the necessary cellular infrastructure to make the ICE concept feasible?”

Link Budget Analysis

We performed a link budget analysis to establish the feasibility of the ICE concept for satellite communications, by leveraging calculation techniques from the 2001 Global Wireless Education Consortium (GWEC) Link Budget Presentation [2] and modeling the results in Analytical Graphics Incorporated (AGI) Systems Tool Kit (STK) [3]. The model was oriented for this specific scenario in a direct line of site configuration with no terrestrial or human tissue obstructions. Notional antenna hardware was modeled for both the satellite (helical coil) and the cell tower (parabolic dish). The transmitter and receiver were both modeled using realistic 1.9 GHz LTE conservative settings.

The goal of the analysis was to ensure feasibility of an executable communication system that provides seamless satellite-to-cell tower communications while operating within FCC approved restrictions.

Antennas

The tower antenna was modeled as a simple parabolic dish, which is an easy design to evaluate and implement that achieves the desired gain pattern with low side-lobes to minimize interference. The satellite antenna is more complex since it requires a similar downward pointing gain pattern from a retractable antenna that can fit into a small satellite form-fit package (Figure 5). Such an antenna was presented in the “Deployable

Helical Antennas for CubeSats" paper [4] presented at the AIAA Technical Conference 2013.

Figure 5: Deployable Helical Antenna

This helical antenna concept offers a high gain, high bandwidth antenna which meets the needs of the ICE application. For purposes of this link budget analysis, notional helical coil antenna parameters were used for the 1.9 GHz frequency. The retractable feature of this helical coil antenna supports the feasibility of implementing such an antenna within the physical constraints of a CubeSat.

Using AGI Systems Tool Kit (STK) version 11.1, a helical antenna was modeled using the following parameters: 1.9 GHz frequency; 10 cm deployed diameter; 55% efficiency; 2 cm turn spacing; 15 turns; and -30 dB back-lobe gain. The results yielded a gain pattern having a 40 degree beamwidth with 17.9 dBi peak gain (Figure 6).

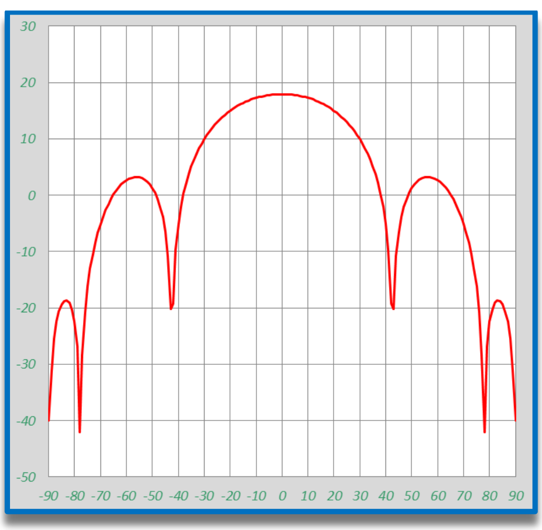

Figure 6: Satellite Antenna Gain pattern

The cell tower parabolic dish was modeled in STK with the following parameters: 1.9 GHz frequency, 21.90 degree beamwidth, 42 cm illuminated diameter, 16 dB main-lobe gain, 55% efficiency, and -30 dB back-lobe gain. This results yield the gain pattern shown in Figure 7.

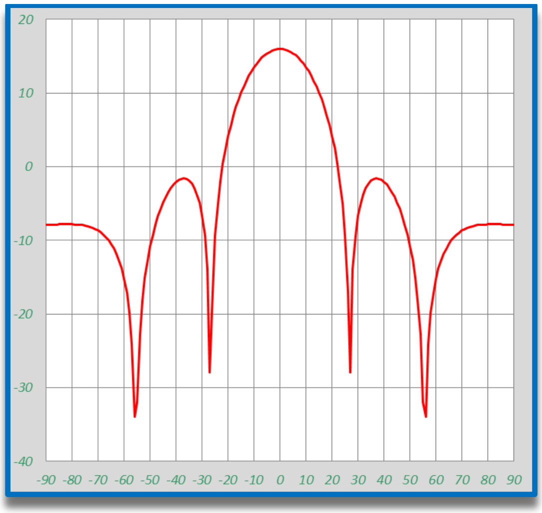

Figure 7: Tower Antenna Gain pattern

The physical diameter of the dish is enlarged to 50 cm to both minimize undesired interference into ICE from external sources and interference from ICE into neighboring cell antennas. In our analysis, the effective illuminated dish surface will still be defined by a 42 cm diameter area of the 50 cm diameter physical dish.

Transmitter/Receiver

A key aspect of our link budget analysis is to assess whether the ICE system can transmit large amounts of data from the satellite down to the ground through the cell towers (the downlink scenario). The value of small satellites is related to their ability to transfer valuable information to the ultimate customers in reasonable times. Albeit a very subjective statement, it will ultimately determine the real effectiveness of these promising collection assets. Although it is important to transmit information such as commands and mission tasking back up to the satellite, the amount of this data is comparatively quite small.

Table 1 identifies the input parameters (yellow highlighted entries) and resulting calculations for the satellite transmitter portion of the link budget analysis.

TRANSMIT	Phone
Freq (GHz)	1.90 GHz
Transmit PA (W)	3.0 W
Transmit Antenna Gain (dBi)	17.9 dB
Transmit Cable Loss Total (dB)	
Transmit Combiner Loss (dB)	
Body Loss (dB)	0.0 dB
Vehicle Loss (dB)	0.0 dB
Other: in building coverage (dB)	0.0 dB
Slow fade margin (dB)	5.4 dB
******** *Calculated* ********	
Transmit PA (dBm)	34.8 dBm
Transmit EIRP (dBm)	
Transmit ERP (dBm)	52.7 dBm
Transmit ERP (W)	186.5 W
Effective Transmit Power (dBm)	47.3 dBm

Table 1: Satellite Transmitter

Similarly, Table 2 identifies the necessary input parameters (yellow highlighted entries) and results for the corresponding receiver at the cell tower which establishes the downlink scenario.

RECEIVE	Tower
Channel BW (kHz)	10000.0 kHz
Ambient Temperature (deg F)	70 deg F
RBS Gain (dB)	24.0 dB
RBS Noise Figure (dB)	4.0 dB
Cable Length (ft)	50.0 ft
Cable Loss per 100 ft (dB/100-ft)	0.767 dB
TMA Gain	12.0 dB
TMA Noise Figure	1.0 dB
C/N (3% BER) (dB)	15.0 dB
Receiver Diversity Gain (dB)	5.0 dB
******** *Calculated* ********	
Receiver Antenna Gain (dBi)	16.0 dB
Ambient Temperature (deg C)	21 deg C
Thermal Noise (Kelvin)	294.1 K
Noise Floor (dBm)	-103.9 dBm
Noise Floor + RBS (dBm)	-99.9 dBm
Receiver Cable Loss (dB)	0.4 dB
Effective Noise Floor no TMA	-99.5 dBm
System Noise Figure with TMA	5.0 dB
Effective Gain of using TMA	-0.7 dB
Effective Noise Floor (dBm)	-98.9 dBm
Body Loss (dB)	
Vehicle Loss (dB)	
Other: in building coverage (dB)	
Min. Radio Input (dBm)	-83.9 dBm
Effective Min. Input (dBm)	-104.9 dBm

Table 2: Cell Tower Receiver

Tables 1 and 2 identify the effective transmitter power at the satellite and the minimum effective input power at the cell tower, respectively. Next, we calculate the effective path loss between the transmitter and receiver, and finally the maximum distance achievable to sustain the successful communication (Table 3).

PATH LOSS	Phone -> Tower
Effective TX Power (dBm)	47.3 dBm
Effective RCV Input (dBm)	-104.9 dBm
Max. Path Loss (dB)	152.2 dB
Max. distance (km)	511.0 km

Table 3: Path Loss

This loss is unaffected by horizontal cell tower terrestrial scenarios that are typically plagued by obstructions and multipath. Our ICE link budget models an unobstructed vertical line of sight scenario that is limited only by range and atmospheric losses. In this scenario, the link budget calculates a maximum allowable distance of 511 km. This is the maximum distance since this calculation is made using the best-case link-budget measurements, max satellite antenna gain to max tower antenna gain. To present realistic link budget coverage, STK was used to model the transmitter and receiver in a real-world scenario. Figure 8 illustrates that a successful link budget is achieved as far as 12 degrees off the cell tower surface normal vector for a 300 km satellite orbit altitude.

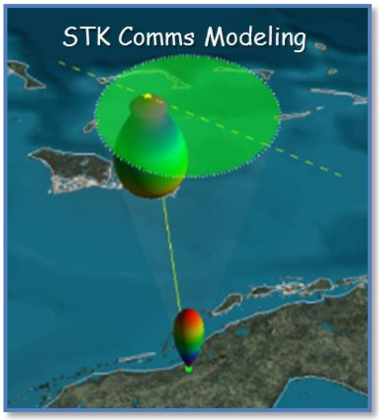

Figure 8: Tower Coverage

LTE data rate throughput calculations were provided by www.3glteinfo.com [5]. Table 4 identifies data rates corresponding to various channel bandwidths, assuming a 64 QAM modulation.

LTE Maximum Downlink Data Rate			
Channel Bandwidth	5 MHz	10 MHz	20 MHz
Subcarriers per LTE symbol	300	600	1200
Data rate (64 QAM) (Short CP)	25.2 Mbps	50.4 Mbps	100.8 Mbps
			www.3glteinfo.com

Table 4: Data Rate

In our link budget analysis we defined the channel bandwidth as 10MHz, but to calculate data throughput we will select a conservative bandwidth of 5MHz. As shown in Table 5, this results in a 25.2 Mbps data rate. A proposed five tower scenario over Illinois, illustrated in Figure 9, yields approximately 240 MBytes of information (Table 5).

5 Towers:		
MAX Channel Bandwidth:	5	*Mhz*
Modulation:	64 QAM	
Bits per symbol:	6	
Duration per symbol:	71.4	*u sec*
Subcarriers:	300	
Data Rate:	25.21	*Mbps*
Comms Duration:	76	*sec*
Data Rate (Mb):	1915.97	*Mbits*
Data Throughput (MB):	**239.50**	*MBytes*

Table 5: Data Throughput (5-Tower Scenario)

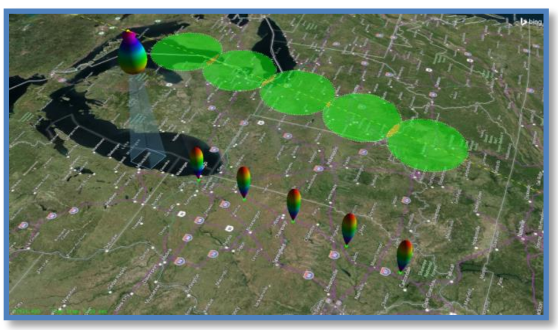

Figure 9: Five Tower Scenario

Cellular Networks

Cell phone services have significantly evolved over the past decade. Advances in telecommunications technology have transformed a simple voice phone into a media storefront. LTE 4G networks are now able to stream video into the palm of your hand. These advances should also benefit the small satellite community.

Ultimately, the goal is to allow a satellite vendor to purchase a satellite-enabled phone that can be integrated into their satellite hardware. To reduce weight, these phones would offer no video interface or antenna, and these phone circuit cards could be easily integrated into a NANOSAT or SMALLSAT chassis. A monthly service fee or data-package fee could be charged, and at least initially, a usage fee may apply.

ICE Software

Firmware is necessary to translate remote commands into satellite operations. Software is necessary to manage satellite tasking, the communication network to support multiple satellite access communications, and the subsequent information flow to and from the satellite (Figure 10).

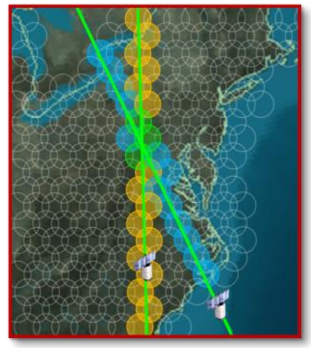

Figure 10: ICE Operations Management

Applications will need to be developed for handheld devices to request collection tasking and to view data products. Ultimately, the goal is to provide an architectural framework (Figure 11) within which academia, commercial industry, or even the ordinary citizen can explore satellite technology. Eliminating the physical ground site and offering a virtual communication framework unleashes the public to explore and invent in an area that was previously controlled by a limited, well-funded private community.

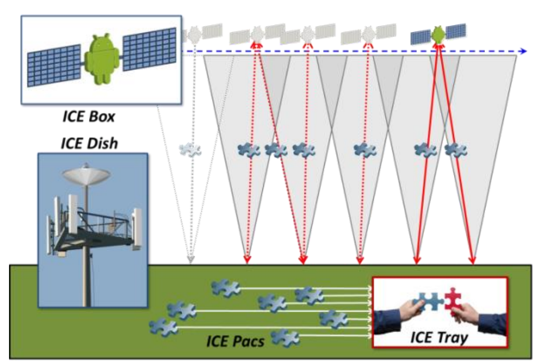

Figure 11: ICE Architecture

APPLICATIONS

Applications for ICE include homeland security, space resiliency, emergency management, natural disasters, monitoring, communications, atmospheric and ionospheric research, sensor calibration, forest fires, weather, land survey, etc. There are many concepts for SMALLSATs, NANOSATs, and PICOSATs, from single satellites to constellations of tens to hundreds of satellites. Legacy communications systems and single pedestal dish antennas would be overwhelmed by the increased demands associated with managing thousands of satellites and systems, monitoring their health, commanding each satellite, and managing the flow of data/information to and from each satellite. Additionally, the legacy large-ground site communications concept is susceptible to terror attacks against critical communication nodes. ICE offers a versatile solution to handle thousands of satellites simultaneously and globally as either the primary or backup communications system for our DoD, civil, and commercial satellite systems.

Just as we leverage the creative minds of industry, academia, and our entrepreneurs to create new small satellite collection systems, we can leverage these same sources to create new applications for ICE. A notable application of ICE technology is space resiliency.

Space Resiliency

As we begin to better understand the threat posed by terrorism and potential attacks on critical infrastructure, ground sites can become potential targets with attacks on these sites having serious impacts to our satellite systems. ICE helps to mitigate this threat by distributing the communications across tens of thousands of cell towers. If any towers were to be damaged, it would have minimal impact to our ability to communicate. Additionally, temporary replacements could be provided in very short time, as contrasted with the loss of a ground site.

Additionally, the threat from Cyber Attack to our cellular and communications infrastructure is currently a major concern. We can leverage much of the current cell phone technology and the preventative techniques employed by the cellular industry to protect ICE. Likewise, encryption techniques currently employed by cellular companies and many software applications offer significant protection.

CONCLUSION

ICE offers a unique capability for large-area unrestricted satellite communications using relatively simple, inexpensive, redundant, and scalable cellular technology. Utilizing the existing cellular network leverages the infrastructure of a massive data communications network to disseminate information. As the number of small satellites and constellations grows, the ICE concept will offer unlimited access. The approach can be applied globally on cell towers or at any broadband internet access point. The legacy dish pedestal approach can only handle a single satellite within its field of view, whereas ICE can simultaneously handle many satellites with a single cell tower; no pointing, no tracking, no prioritizing, no man-in-the-loop. Just as the internet and cell phone technology offered people unrestricted access to each other, ICE extends the reach of these two technologies to offer unrestricted access to space.

Since our initial presentation on the ICE concept to the SmallSat Conference in 2014 [1], we performed a conservative link-budget-analysis and found that a 25.2 Mbits/sec data rate was achievable that yielded 240 Mbytes of data over a period of 76 seconds (the time to pass through 5 cell towers). As cellular signal processing technology advances, we can expect a significant increase in data throughput.

Riverside Research has a rich history of bringing technology-based solutions to our customers in the most cost effective manner, especially in the satellite collection tasking and mission management arena. As a not-for-profit company, Riverside Research has supported the US Government for nearly five decades and looks forward to meeting future challenges.

References

[1] Ploschnitznig, J. 2014. "The Small Satellite Integrated Communication Environment (ICE)," Proceedings of the AIAA/USU Conference on Small Satellites, Advanced Technologies-Communication, SSC14-IX-8. http://digitalcommons.usu.edu/smallsat/2014/AdvTechComm/8/.

[2] Johnson, E. 2001. "Link Budgets for Cellular Networks", presentation at the GWEC 2001 conference hosted by WNS Technical Education, AT&T Wireless.

[3] Systems Tool Kit is an Analytical Graphics Incorporated software engineering product. https://www.agi.com/products/engineering-tools

[4] Olson, G., Pellegrino, S., Banik, J., and Costantine, J. "Deployable helical antennas for cubesats", 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Structures, Structural Dynamics, and Materials and Co-located Conferences, (AIAA 2013-1671)

[5] http://www.3glteinfo.com/lte-data-rate-throughput/

Further details regarding the ICE system and technology are disclosed in U.S. Patent No. 8,751,064 B2, entitled "Methods and Systems for Satellite Integrated Communications," issued June 10, 2014.