WHITE PAPER

Satellite telemetry boosted by new chips to enhance & secure the radio link (TT&C)

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TELEDYNE e2v | Semiconductors
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ABSTRACT

Telemetry, Tracking, and Control (TT&C), is a critical lifeline to satellite network control. TT&C is responsible for the transmission of telemetry data from the satellite to ground stations, tracking position and movement, as well as sending operational commands to the satellite. The purpose of TT&C is to ensure satellites perform correctly. Ultimately, momentary failure of the TT&C system can lead to mission loss. Demands upon TT&C are increasing rapidly. New solutions are required to handle the anticipated increase of on-orbit traffic as well as the expanding data throughputs of space-borne infrastructure. This summary details some of the trends driving change along with technologies emerging to advance TT&C design.

THE PURPOSE OF TT&C

Successful satellite operations comprise three principal aspects performed by dedicated on-board hardware – the TT&C unit, these are:

- Telemetry: General health and operational status monitoring via the collection and processing of various spacecraft sub-systems' sensed conditions.
- Tracking: Precision spatial positioning detection via the monitoring of key ranging data
- Control: Operational control from the execution of commands received from the ground station network.

Some advanced systems are already evolving autonomous operation - many of the control functions now require less ground intervention. Increasingly, reliance on software defined radio techniques, combined with the need for semi-autonomous operations is pushing future TT&C designs to enhance on-board processing performance whilst leaving a route to dynamic (over-the-air) system re-programming.

CHALLENGES FOR TT&C IMPLEMENTATION

Implementing TT&C services requires significant end-to-end engineering expertise for success. The full complexities of the design of these systems is beyond the scope of this article, however microwave engineers will be familiar with many of the topics facing TT&C designers. These include signals coding, modulation, multiplexing, link and interference analysis – as well as the design of representative TT&C software simulators. Increasingly end-to-end link security is key, requiring expertise in data encryption and authentication.

LOCATION OF TT&C SYSTEMS

For the TT&C system, telemetry conveys the operational and health status of the satellite, telecommands convey actions that the ground-based mission operations control (MOC) to be performed. Finally, on-orbit information delivers the space environment, position, and velocity of the satellite, which impacts satellite tasking. Though not so with high throughput (HTS) communication satellites, in many space missions, the TT&C system is the principal application data communication path - satellite to MOC. Thus, application considerations set latency and data throughput expectations on TT&C performance.

Over time, TT&C systems have grown in complexity, originally comprising relatively simple ground-based MOC with distributed ground station resources across planet Earth. Increasingly, to enhance the continuity of connection to the MOC, terrestrial stations, have extended to include ocean-based resources, and then upwards into a variety of space-based tracking and data relay satellites (TDRS). In addition, TT&C operations are aided by access to global satellite navigation services (GPS & Galileo), together with the corresponding communication infrastructure.

THE TECHNOLOGIES BEHIND TT&C

The evolution of satellite TT&C technologies covers three critical aspects: baseband equipment, antenna units, and TT&C platform

Baseband equipment: Early TT&C generations comprised analog design techniques heavily reliant on carefully designed signal filters. Originally the functions of TT&C were carried out by discrete functional elements. Obviously, TT&C equipment based on analog device design was bulky and hard to upgrade. With rapid advancements in digital circuits and programmable device technology - especially over the last decade, the major TT&C functions can now be performed in one unified design deploying field programmable gate array (FPGA) or digital signal processing (DSP) chips. Moreover, these functions can now be upgraded at the appropriate time with advances made to coding algorithms via over-the-air (OTA) updates.

Increasingly, digital device performance is such that some companies consider the next generation of SDR design will soon migrate to direct conversion approaches whereby microwave signal content is extracted directly from microwave RF signal without recourse to frequency down conversion (heterodyning). This progression in capabilities, that moves many of the design challenges into the digital domain is a welcome paradigm shift since it provides TT&C system designers a broader variety of robust design approaches. Equally, this beneficially impacts on the interplay of SWaP factors (size, weight and power).

Antenna Units: A typical TT&C antenna is a parabolic dish. It is convenient and has the advantage of high gain, combined with relatively low manufacturing and maintenance cost. But with the gradual increase in the number of tracked satellites, mechanically scanned antennas (using servoed motors) are increasingly unsuitable. Enter one of the most important innovations in antenna design, the development of electronically scanned, flat phased array antennas (PAAs). PAAs receive increasingly more attention for satellite applications since they can generate multiple RF carrier beams and consequently track multiple satellites at the same time. Compared to mechanically scanned antennas, PAAs achieve fast beam scanning without physical rotation and track multiple targets simultaneously. Just as semiconductor advancements are improving baseband electronics; those same advancements enable electronic beam steering for enhanced RF link agility in TT&C systems.

TT&C Platforms: Original first-generation satellite TT&C stations were built as relatively inexpensive ground-based infrastructure (see figure 1). However, their contact time (fly-by window) is short lived, so it is necessary to deploy TT&C stations scattered around the world for missions requiring higher contact. This though is an unrealistic expectation for many countries and organizations wishing to operate independent space systems. Solving this, TT&C has migrated in two directions:

1. initially a move to provide ocean-based TT&C resources and latterly,
2. working towards space-based TT&C using tracking and data relay satellites (TDRS).

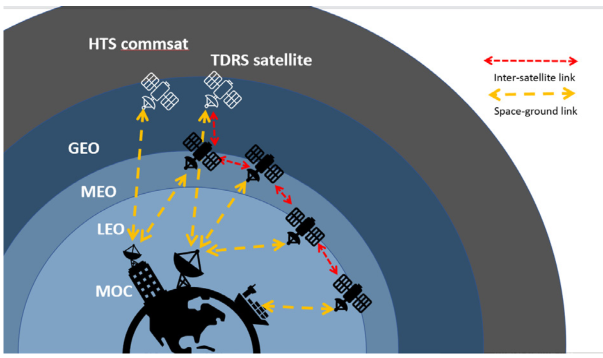

Figure 1: TT&C connectivity routes

Obviously, both advancements emphasise the increasing cost and complexity of space-borne assets. Furthermore, this situation is set to worsen over the decade, not least because of the rapid rise of private entrepreneurship re-shaping the space race. Several organizations are already working to deliver vast low earth orbiting (LEO) satellite constellations to provide universal internet coverage (e.g. SpaceX). In these situations, TT&C becomes an even more critical operational challenge.

FUTURE TT&C CHALLENGES

Managing large satellite constellations via TT&C in future will further stress existing resources. Problems arising will include:

1. Finding methods to ensure maximum data transfer capacity during short fly-by windows suggesting the use of advanced cognitive multimode radio links. Moreover, to expand contact time, TT&C may increasingly migrate to space-based infrastructure such as TDRS.
2. Reducing the transmission of redundant telemetry data to maximize transport of mission critical data. This suggests the deployment of on-board, autonomous data parsing using artificial intelligence (AI).
3. Pressure on radio spectrum availability fuels a need for smarter agile radio systems in general and the arrival of microwave direct conversion technology is a timely development.
4. No mater the mission profile, increasingly operational security is a central concern of infrastructure providers. Preventing unauthorized access to expensive, on-orbit assets demands rugged security mechanisms and data encryption.

Given the above factors, TT&C looks set to become a networked system where elements of telemetry and tracking management are handed-off from the MOC to semi-autonomous flight planning within the satellite constellation itself. It seems a reasonable objective that a satellite system be able to maintain orbit and relative positioning with a suitable access to inter-constellation ranging sensors and on-board inertial measurement units.

ON THE IMPACT OF MODERN RADIO DESIGN

Different digital modulation schemes in the form of Adaptive Coding and Modulation (ACM) provide a route for enhancing satellite fly-by data throughput. The ability for a channel to transfer data is determined by the signal to noise performance. When applying digital modulation, it is possible to substantially increase the number of encoded symbols per unit transmission time (see figure 2).

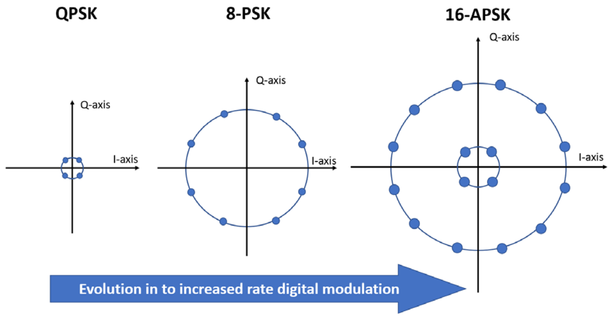

Figure 2: Evolution in digital modulation for increased spectral efficiency & data throughput

APSK - A SOLUTION FOR SATELLITE LINKS

APSK (or Amplitude Phase Shift Keying) offers an ideal modulation scheme for satellite transmission. It has higher spectral efficiency (bits per symbol) than quadrature phase shift keying (QPSK) but is more resistant to distortion than quadrature amplitude modulation (QAM). APSK offers the best of both worlds. For APSK, the symbol points are configured to land on concentric rings of constant amplitude (see Figure3).

Both QAM and APSK provide more bits per symbol than QPSK, allowing more data to be sent in the same channel bandwidth. But unlike QAM, APSK states occur in concentric rings, such that symbol points in each ring react in the same way to compression. This provides two benefits. Firstly, that compression tends to have less of an effect on the spacing between states, and thus states are easier to distinguish during demodulation.

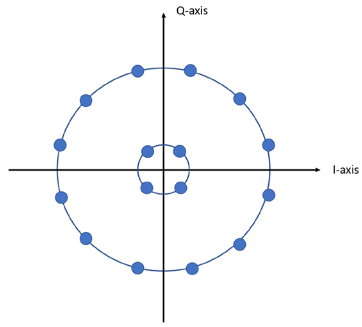

Figure 3: 16-APSK constellation

The second advantage is that APSK lends itself to pre-distortion that varies the offset between constellation rings before transmission, counteracting the effects of distortion thereby enhancing the received signal strength. With dynamic pre-distortion, the signal received is monitored with the results fed back to the pre-distortion circuitry for continuous adjustment. Peak to Average Power Ratio (PAPR) is another design consideration. This parameter defines the ratio of the highest transmit power the transponder amplifier delivers, relative to average power. This constraint determines the amount of data that can be sent, since the average power sets system boundary conditions (such as power and thermal limits). However, the output power for a particular modulation, depends on the transient characteristics of the modulated signal. It turns out, APSK enjoys a modest advantage over QAM making it especially suited to space application.

The performance afforded by flexible coding (ACM) enables enhanced contact between the TT&C and MOC for an extended period as well as providing dynamic optimization of the up/downlink throughout the satellite's fly-by window (see figure 4). Theoretically, even higher data rates might be enabled by optical links. But optics represent a challenge for steering and locking to line-of-sight conditions. Optical fly-by tracking remains a thorny design issue.

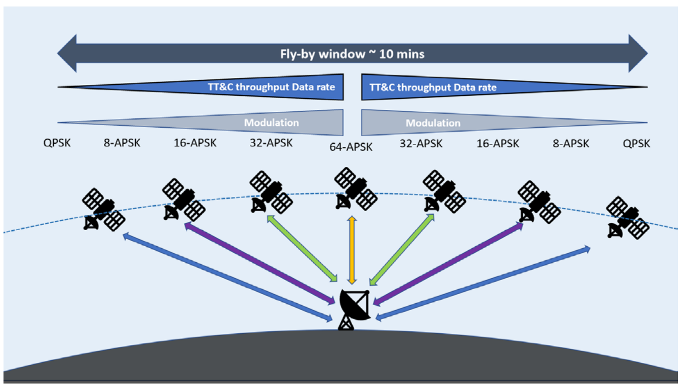

Figure 4: Optimized fly-by data throughput using dynamic ACM

Being able to enhance the performance of future TT&C systems relies on exploiting novel ACM techniques using advanced SDRs. That itself is heavily reliant on the availability of a new crop of leading-edge semiconductors.

TT&C HARDWARE CONSIDERATIONS

State-of-the-art microwave radio design used for TT&C is normally focused in the L-, S- and C-bands – between 1 to 8 GHz. Because of the large RF bandwidths, by far the majority of TT&Cs in production rely on traditional heterodyne designs (for frequency down-mixing) and they remain heavily invested in digital baseband sampling of the final intermediate frequency (IF). Arguably, given bandwidth constraints of existing data converters, it has been impossible to conceive of direct conversion technology all the way into the Ku-band. Today however, that is just around the corner.

Broadband data conversion: Increasingly faster process technologies are supporting broadband operation that now reach close to double figures gigahertz bandwidths, e.g the EV12AQ600 achieves a boosted 6.5 GHz bandwidth and can sample signals at up to 6.4 Gsps (in 4-phase time-interleaved mode). Teledyne e2v, the developers of the innovative EV12AQ600 12-bit ADC included a useful front end cross-point switch that facilitates multi-channel, time-interleaved operation to create a extremely flexible SDR front-end.

Increasingly, the company is pushing its technology to the limits of possibility and extending upper end operation ever closer to full microwave direct conversion - working up to and beyond the limit of ku-band. Its latest development includes the pre-launched EV10AS940 an integrated 12.8 Gsps sampler with 33 GHz -3 dB analog input bandwidth. Much of Teledyne e2v's development focus has been paying close attention to modern radio architectural demands. That rigorous attention to customer need has led the development of a license-free, low overhead serial interconnect system, designated ESIstream. ESIstream is capable of data throughput rates above 12 Gsps and supports a broad range of digital processing components including FPGAs available from a variety of vendors. The protocol offers low deterministic data latency, minimal hardware overheads, and helps to deliver cross-system synchronization.

Electronic beam steering enables phased array antennas. For this reason, Teledyne e2v developed a novel method of guaranteeing synchronous operation across complex multi-channel designs. Deterministic synchronization is assured across multiple ESIstream data lanes. More importantly, at the front end, a simple system synchronization signal can be cascaded across data converter chains to guarantee both the avoidance of metastability[1] and simultaneous sampling; thus, ensuring that critical signal phase information, for spatial accuracy, is preserved throughout the system.

The final way a device like the EV12AQ600 helps, is by supporting variable rate sampling through the embedded sample interleaving circuit. Each ADC core can be clocked at up to 1.6 Gsps enabling a pair to be opposite phase sampled at an aggregate 3.2 Gsps. Interleaving all four cores with 4-phase clock enables a single channel sampling at 6.4 Gsps.

PolarFire FPGAs: One of the most advanced and versatile digital processing systems for space operations are the PolarFire® family of FPGAs produced by Microchip Technology. These products have a focus on security features combined with low power operation and are now able to be used in conjunction with the EV12AQ600 since license-free, ESIstream drivers have been released (check out: ESIstream official - ESIstream 14B/16B package).

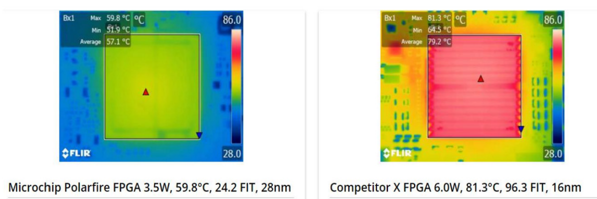

Figure 5: Thermal comparison PolarFire® and a competing alternative

PolarFire devices offer several desirable features unavailable elsewhere, complimenting their use in advanced space-borne software-defined radios.

[1]***metastability*** *describes the ability of a system to persist for unbounded time in an unstable equilibrium state*

These benefits include:

- Half the power of conventional SRAM FPGAs with similar complexity, lowers the thermal design overhead (figure 5)
- Military-grade cyber-attack & anti-tamper features including licensed Rambus DPA countermeasures[2]
- Immune to configuration upsets through fault tolerant design
- Radiation tolerant 100 k total ionizing dose (TID)
- 24 x 10.3125 (or 12.7 high-speed option) Gbps serdes lanes, support multi-channels data transport

Radiation tolerant (RT) PolarFire® FPGAs are non-volatile field programmable gate arrays fabricated in United Microelectronics Corporation (UMC) 28 nm technology. These FPGAs offer 481K Logic Elements (LEs), 480 math blocks (DSP) and 33 Mbits of embedded Static Random Access Memory (SRAM). Incidentally, the SRAM can also be protected using error correction codes (ECC) which will be important under space-conditions to avoid working with corrupted data.

Security is a key factor differentiating PolarFire FPGAs. The family provides integrated dual physically unclonable functionality (PUF) combined with 56 KB of secure, non-volatile memory (sNVM) for encryption key storage. Moreover, built-in tamper detectors and active DPA countermeasures work to provide military-grade security. Equally, in-orbit programming, essential to enabling reconfigurable SDRs, has been extensively tested and validated[3].

EV12AQ600 AND POLARFIRE - AN IDEAL PARTNERSHIP FOR ENHANCED SPACE GRADE TT&C

A recent tutorial has been published detailing the pairing of an EV12AQ600 FMC card with an MPF300T-1FCG115E2 PolarFire processor board (figure 6). This environment helps accelerate development flows allowing users quick system familiarization together with building readiness for initial prototype engineering. The tutorial works through how to set-up the FPGA board, and a Libero SoC IDE project that exploits the embedded ramp waveform generator within the EV12AQ600. Moreover, you will discover how to extract sample date from the interconnected boards.

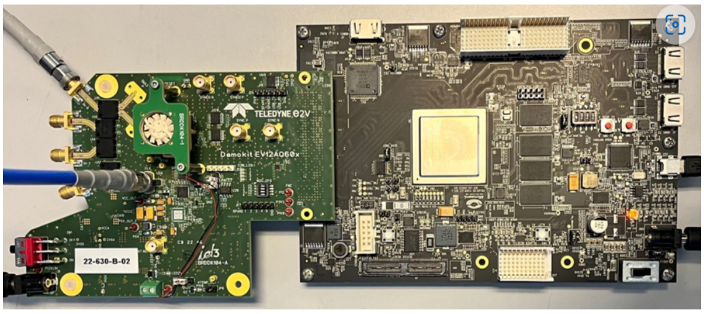

Figure 6: PolarFire FPGA card with EV12AQ600 FMC combination

The combination of PolarFire FPGA and EV12AQ600 advanced front-end digitizer, represents a powerful experimental platform for next generation TT&C SDR design. The development resources now available, support several future SDR configurations and can evaluate various ACM configurations. Furthermore, this system accelerates time to market.

[2]Rambus DPA countermeasures technology used to prevent side channel attacks.

[3]RADECS 2021: In Orbit Programming and SEE characterization of the Microchip RT PolarFire® FPGA Fabric. N. Rezzak, Member, IEEE, R. Chipana, C. Lao, G. Bakker, Member, IEEE, J. Mccollum, Member, IEEE, F. Hawley, Member, IEEE, K. O'Neill and E. Hamdy, Senior Member, IEEE

ARTICLE LINKS

EV12AQ600 product page: https://semiconductors.teledyneimaging.com/en/products/data-converters/ev12aq600/
ESIstream official - ESIstream 14B/16B package: https://www.esistream.com/package/esistream-14b16b-package
PolarFire FPGA family: https://www.microchip.com/en-us/products/fpgas-and-plds/fpgas/polarfire-fpgas
PolarFire lowest total power: https://www.microchip.com/en-us/products/fpgas-and-plds/low-power
Rambus DPA countermeasures: https://www.rambus.com/security/dpa-countermeasures/licensed-countermeasures/
EV12AQ600 with PolarFire evaluation tutorial: https://youtu.be/1iXG7gQjy90

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