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A Comparative Study on various Flight Termination System Technologies

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ABSTRACT

In a test range, a Flight Termination System (FTS) plays a prominent role in protecting range and flight personnel along with surrounding area population in case the flight vehicle is out of its trajectory range and possesses a threat to surrounding. An efficient FTS should possess high Signal to Noise Ratio, link robustness to ensure reliable communication between ground transmitting and onboard receiving systems and should be immune to interference. This article presents a detailed report on the requirement and features of FTS & technologies used in it. Techniques such as tone based, code based and Code Division Multiple Access (CDMA) are considered. Analysis of RF spectrum, gain and noise figure measurement, channel power etc are presented. Advanced methods like Enhanced Flight Termination System (EFTS) and Autonomous Flight Termination System (AFTS) are also considered which show supportable and upgradable technologies, better range understanding, unique vehicle id & higher data rate. AFTS being self-reliant provides superior performance in terms of GPS, launch responsiveness, multiple flight vehicle control and auto pilot.

Keywords: Flight Termination System (FTS); Code Division Multiple Access (CDMA); Signal to Noise Ratio (SNR); Enhanced Flight Termination System (EFTS); Autonomous Flight Termination System (AFTS)

1. INTRODUCTION

Flight Termination system (FTS) is an integrated system which provides redundant explosive assemblies capable of terminating the flight of airborne missiles or flight vehicles when they deviate from the designated path. FTS[1-2] must render each power stage and any other propulsion system, including part of payload. It protects range and flight personnel along with surrounding area population. A newly developed missile system has to be tested and to be proven. Many aspects bring out the need for FTS like user demonstration of missiles, workmanship errors, if reliability of systems are up to mark or not, storage and time variant effects of systems. FTS has various subsystems for specific command generation, carrier modulation and proper amplification[3] before radiating the signal through antenna as shown in Fig. 1.

The process ensures a robust wireless communication between ground FTS and on-board missile reception system. On-board command reception system[4-5] takes control of the flight vehicle and performs specific operation according to the required command received. The entire technology should be cost effective and reliable enough to support both ground and on-board system in order to have reverse technology in the on-board package.

Before the test of flight, considerations must be taken into account like the reliability where hardware or software failure rate and redundancy is measured, choice of propellants as it affects the blast and toxic analysis, trajectories for population safety and the selection of range as it affects ground, sea and air hazard zones. FTS is controlled by Range Safety Officer (RSO) remotely. Range safety ensures protection of people and

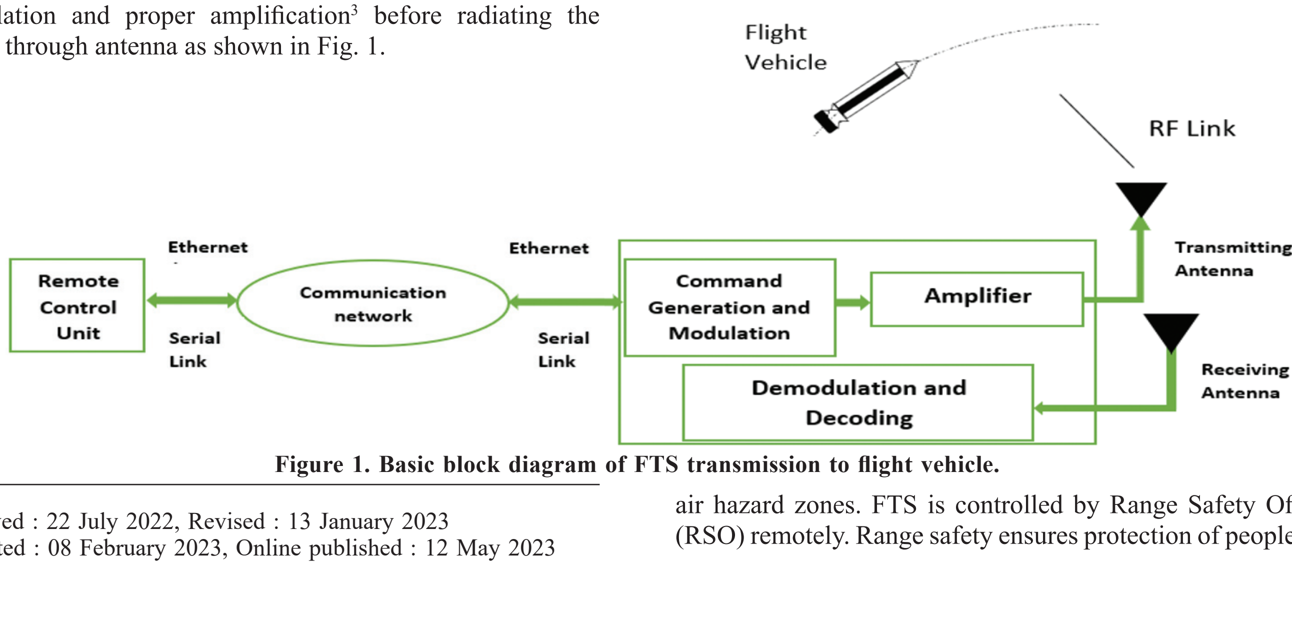

Figure 1. Basic block diagram of FTS transmission to flight vehicle.

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assets in the range and outside. RSO decision depends upon a number of factors like booster chamber pressure, destruct lines, height and speed indicators, visual observation, electro optical tracking instruments data[6], radar data[7], telemetry[8] data etc.

This article includes features and observing parameters of FTS along with different technologies used according to the scale of complexity. Comparison among technologies is also presented. Different technologies from traditional human in loop to artificial intelligence, autonomous techniques are used in FTS. The progress in technologies includes GPS aiding for tracking, autopilot, timing source and decision logic, use of multiple vehicles at once, reduction of ground based flight control personnel, cost cutting and reduction in use of ground stations to avoid plume attenuation.

Further proceedings in the article are as follows. Section II contains the desired parameters required for FTS design. The failure modes of flight vehicle, requirements and features of FTS are discussed in section III. Section IV elaborates the different technologies used in FTS till date and their performance results. Section V compares among the techniques, their methods and system complexity level with requirement. Section VI concludes the discussion.

2. DESIRED PARAMETERS TO BE OBSERVED FOR FTS DESIGN

2.1 Single Fault Tolerance, Redundancy & System Impedance

FTS would not allow a single failure point that affect anyway in its functioning, monitoring of the system during flight or make any unintended termination of the system that would endanger the public. FTS needs to have redundant components which are functionally independent of each other so that failure of any system would transfer the control to the backup unit providing ceaseless operation. The components, connectors and system should be impedance matched for maximum power transfer and efficient performance.

2.2 Optimum Transmitter and Receiver to Avoid Additive White Gaussian Noise

The designed system has to have good noise rejection capacity[9]. The demodulator should have proper correlation and matched filter to produce received signal. The chosen transmission technique should be thoroughly focused so that adequate receiver design[10] is possible. The system should have high S/N ratio. Receiving system should be compact and should take less space with efficient working capability on flight vehicle. If the frequency deviation of frequency modulated white noise RF signal is 12 dB or above the threshold value[11], then the receiver will block the input.

2.3 Sensitivity and Antenna

A reliable receiver system requires command signal strength at electromagnetic field intensity of 12 dB or above the lower bound. Antenna in FTS system needs to have bandwidth twice[12] that of the total combined tolerances of every other system so that it could involve the channel power of each system. The parameters to consider while designing an antenna are frequency range, input impedance, VSWR, axial ratio, transmitting and receiving power and types of polarization.

2.4 Decoder Channel Bandwidth & out of Band Rejection

The receiver decoder must provide a reliable recognition of command signal when subject to ground transmitter tone frequency and frequency deviation variation. The decoder in on-board receiver must be designed in such a way that it would decode the command signal with respect to any transmitting frequency or any variable transmitting parameters. Before use in actual vehicle, the decoder needs to be tested and validated and the structure should be ruggedized. The implementation logic must be one time so that it will receive the signal from its core system and reject any unwanted or outer band signal. Receiver will reject the signal if it is 8 times of its operational bandwidth.

3. REQUIREMENTS AND FEATURES OF FTS

3.1 Failure Modes

There are a few factors which can lead to the failure of flight vehicle like when the engines get locked in extreme position, control surface gets locked, failures of multiple actuators, incorrect generation of command etc. These can lead the flight vehicle to move out of the safety corridor of the launch corridor and need to be immediately aborted. The safety corridor is decided according to the capability of the failure mode analysis of the flight vehicle.

3.2 Features of FTS

Commands transmitted from ground system gain control over the on-board package in the flight vehicle[13]. To maintain redundancy it should have a positive destruction. The termination must produce small pieces of unstable element which would make impact within a small footprint. FTS must control the disposition of burning propellants, radioactive and toxic materials. Safety lockouts like SAFE and ARM devices, timers are incorporated for no accidental destruction.

Features of FTS include physical separation of redundant systems from other vehicle systems, inadvertent separation of destruct system from solid motors, segregation of cryogenic propellants, both engines shutdown, destruct capability on liquid propellant vehicle and capability for complete and thorough end to end testing.

3.3 Approval of FTS

In component level, FTS approval depends on qualification testing, acceptance testing and certification testing. Qualification testing provides the confidence that the system can withstand any operational environment. After qualification testing, the acceptance testing checks the confidence of production units to prove workmanship.

After acceptance test, certification testing is typically performed on critical component before launch of flight vehicle. This test is performed on onboard receiver system. In system level, assembly and checkout tests are done before 30 days of launch to verify each component and take actions on any developed problem. It provides end to end testing. Pre launch checks are final tests which are done prior to launch. It also verifies each device settings and functionality thoroughly. 0.999 @ 95 % confidence is the reliability goal of FTS.

4. LITERATURE REVIEW

The first FTS developed in 1950s was analogue tone based system. It used audio tones of different frequencies to generate the message signal. As technology proceeded, systems were modified in digital platforms. In 1986, tone digital systems and in 1996, PCM/FSK/FM systems came by. To control multiple flight vehicles, Code Division Multiple Access (CDMA) systems are used for modulation. Further, a digital encrypted system called Enhanced Flight Termination System (EFTS) came up which used IRIG and High Alphabet (HA) standards. At present, research and development of an Autonomous FTS (AFTS) is going on. GPS and navigation sensors for navigation and tracking and autopilot are some of the features of AFTS.

Now we screen various technologies used in FTS and look at their performance analysis in test range.

4.1 Tone Based System

As the name suggests, this system is based on the use of standard tones[14] defined by the Inter Range Instrumentation Group (IRIG) further known as Range Commander Council (RCC). The commands are generated from any of the 1 to 20 IRIG tones in a combination of 3 or more in specific analogue encoders.

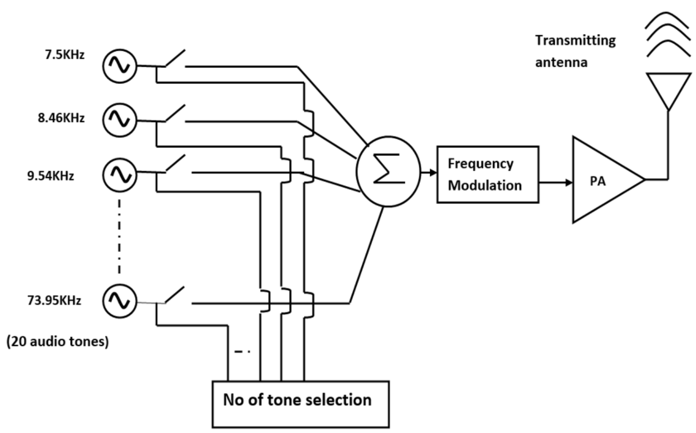

Figure 2. Transmitter block diagram for tone based system.

The generated message signal X(t) is the addition of 3 sinusoidal tone wave forms $x_1(t)$, $x_2(t)$, $x_3(t)$.

$$X(t) = x_1(t) + x_2(t) + x_3(t) = A_m\left[\cos\omega_1 t + \cos\omega_2 t + \cos\omega_3 t\right] \quad (1)$$

where, ω_1, ω_2 and ω_3 are the 3 tone frequencies. Then the generated message signal is up converted using frequency modulation (Fig. 2).

The instantaneous frequency $\omega_i(t)$ for FM modulation[15] will be represented as

$$\omega_i(t) = \omega_c + K_f X(t) = \frac{d\theta(t)}{dt} \quad (2)$$

where, $\omega_i(t)$ is the angle, K_f is frequency sensitivity and ω_c is the carrier frequency

$$\theta(t) = \int_{-\infty}^{t} \left(\omega_c + K_f X(t)\right) dt \quad (3)$$

So the generated FM signal is represented by:

$$FM(t) = A_c \cos\{\theta(t)\} = A_c \cos\{\omega_c t + K_f \int_{-\infty}^{t} X(t)dt\} \quad (4)$$

$$FM(t) = A_c \cos\{\omega_c t + 2\pi K_f A(\frac{\sin\omega_1 t}{\omega_1} + \frac{\sin\omega_2 t}{\omega_2} + \frac{\sin\omega_3 t}{\omega_3})\} \quad (5)$$

At the time of reception, the modulated signal is passed through a mixer where it is multiplied with the carrier signal of local oscillator. (Fig. 3)

$$S(t) = FM(t) * A_{LO}\cos\omega_{LO} t = \frac{A_c A_{LO}}{2}[\cos\{(\omega_c + \omega_{LO})t + 2\pi K_f A(\frac{\sin\omega_1 t}{\omega_1} + \frac{\sin\omega_2 t}{\omega_2} + \frac{\sin\omega_3 t}{\omega_3})\} + \cos\{(\omega_c - \omega_{LO})t - 2\pi K_f A(\frac{\sin\omega_1 t}{\omega_1} + \frac{\sin\omega_2 t}{\omega_2} + \frac{\sin\omega_3 t}{\omega_3})\}] \quad (6)$$

The generated signal is passed through a low pass filter (LPF) having cut off frequency ω_{L0}- ω_C. The in-phase and quadrature phase components of signals $S_I(t)$ and $S_Q(t)$ are:

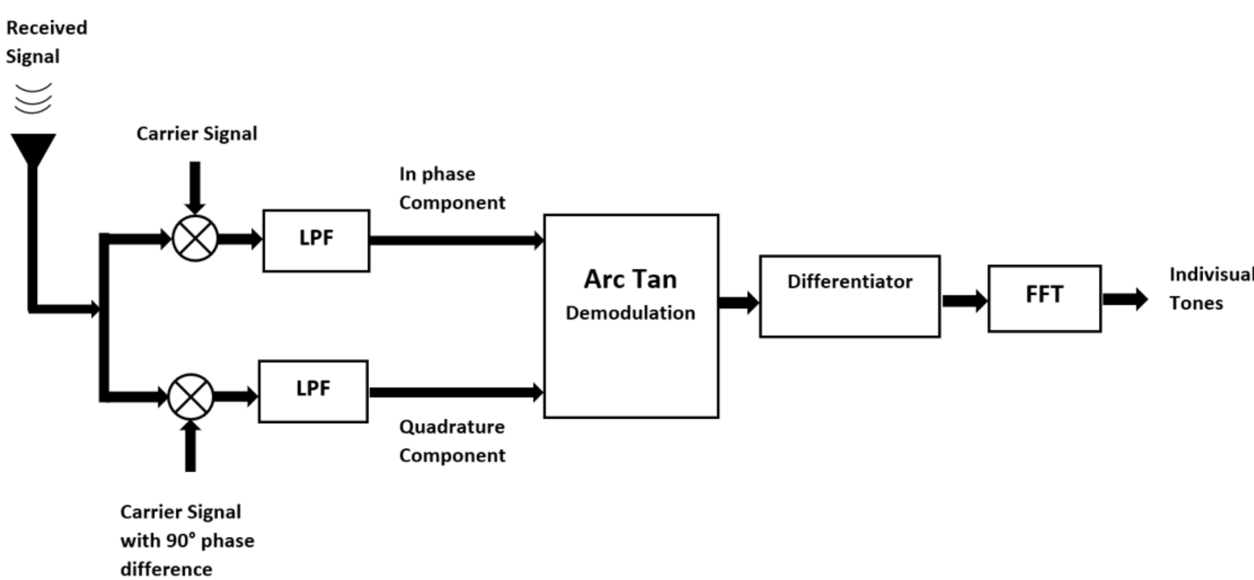

Figure 3: Receiver block diagram for tone based system.

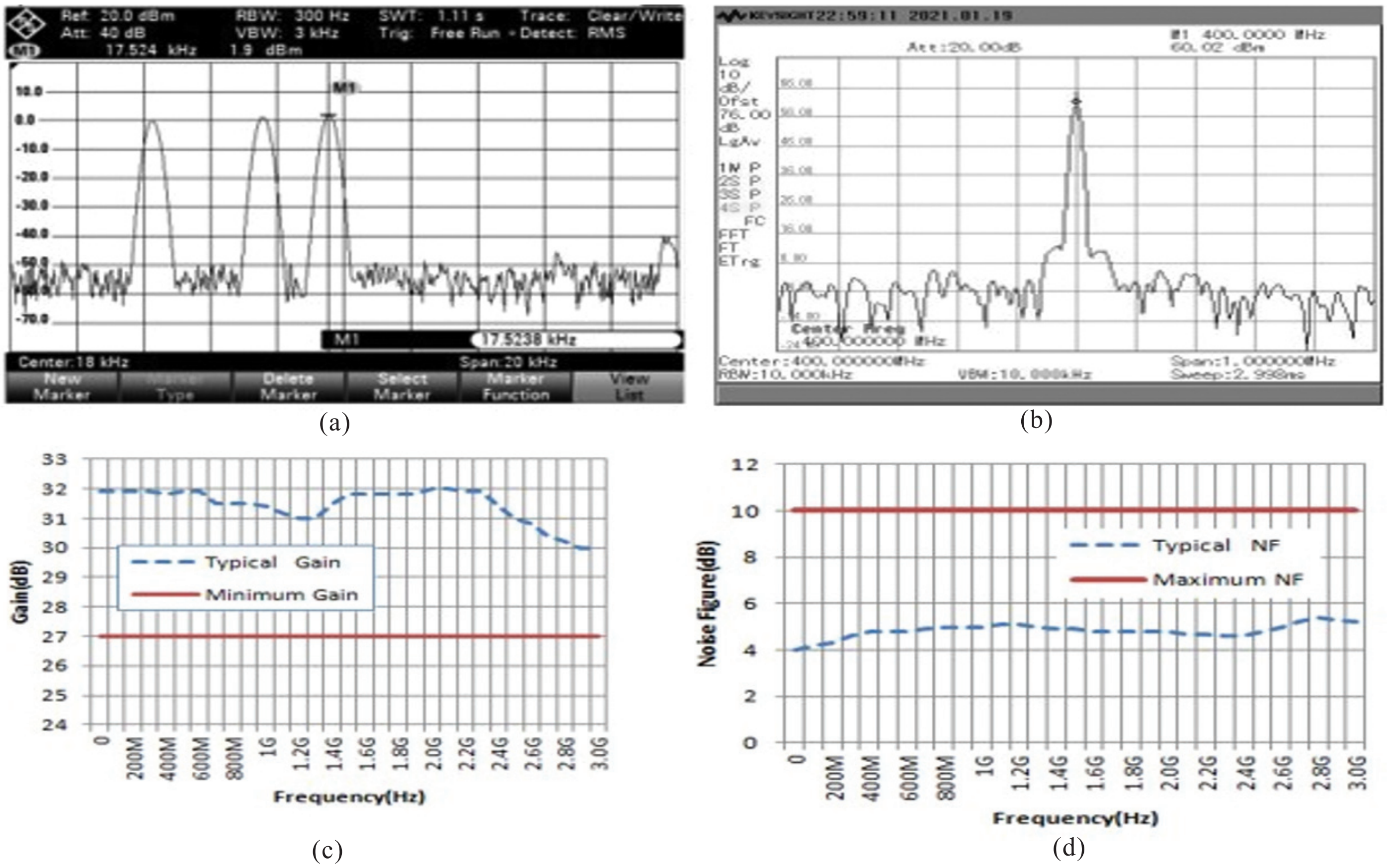

Figure 4. (a) Baseband spectrum after mixture of 3 tones, (b) RF spectrum, (c) Gain measurement, and (d) Noise Figure measurement.

$$S_I(t) = \frac{A_c A_{LO}}{2}\cos\{2\pi K_f A(\frac{\sin\omega_1 t}{\omega_1} + \frac{\sin\omega_2 t}{\omega_2} + \frac{\sin\omega_3 t}{\omega_3})\} \quad (7)$$

$$S_Q(t) = \frac{A_c A_{LO}}{2}\sin\{2\pi K_f A(\frac{\sin\omega_1 t}{\omega_1} + \frac{\sin\omega_2 t}{\omega_2} + \frac{\sin\omega_3 t}{\omega_3})\} \quad (8)$$

By using the arc tan demodulation technique,

$$\varphi(t) = \arctan\left(\frac{S_Q(t)}{S_I(t)}\right) \quad (9)$$

where, φ is the phase of the signal. The output of differentiator is:

$$\Delta\varphi(t) = \frac{d\varphi(t)}{dt} = 2\pi K_f A\{\cos\omega_1 t + \cos\omega_2 t + \cos\omega_3 t\} \quad (10)$$

From this, the original message signal X (t) is recovered. The original message tones $x_1(t)$, $x_2(t)$, $x_3(t)$ are recovered by performing FFT operation.

The performance of tone based FTS is done after completion of specific tests.

Figure 4(a) shows the baseband spectrum observed in spectrum analyser after mixing of 3 tones and Fig. 4(b) shows the RF spectrum.

It is seen that parameters like gain and noise figure measurement are linear in specific frequency range of operation (Fig. 4(c) and (d)). One of the important features of this system is its simpler circuit design for transmission and reception. It provides link robustness and good capture ratio. It does not have any encryption and error correction mechanism which lead to the development of secured code based system.

4.2 Secured Code Based System

A code based system uses command codes instead of particular tone frequency. The command codes[16] can vary for different time being. The desired commands are generated at the encoder as a sequence of N binary bits. Command code is added with unique frame synchronization bits and parity bits to shape the complete frame. This enables frame reorganization and rejects in case parity does not match. The frame bits are encoded with Manchester encoding scheme where bit rate

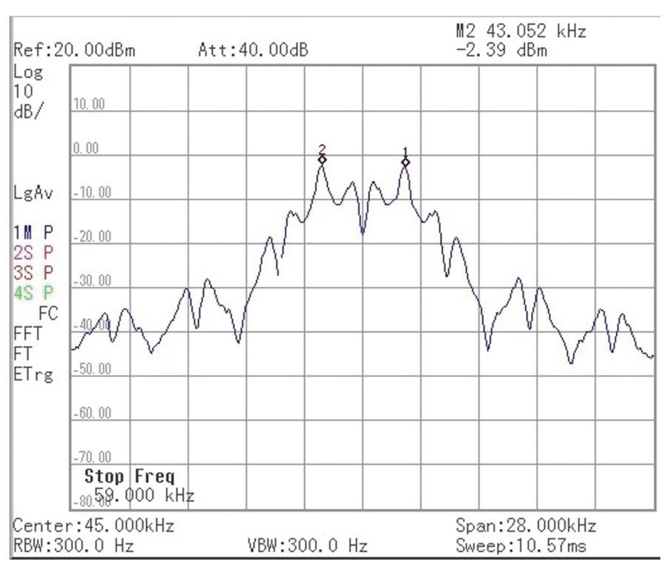

Figure 5. BFSK signal observed in spectrum analyser.

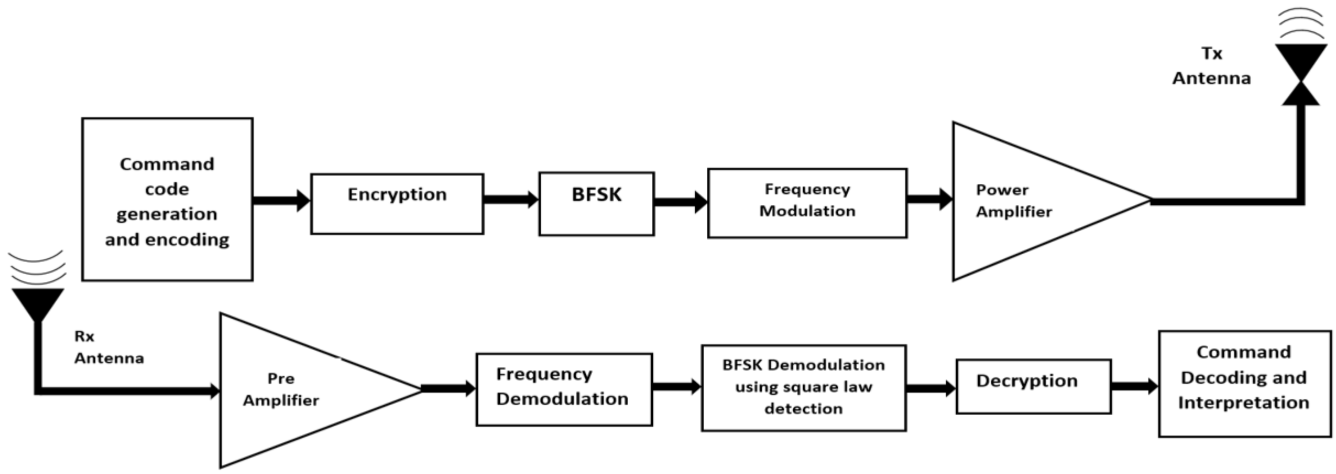

Figure 6. Transmission & reception in code based system.

gets doubled for each frame. By using encoding scheme, the signal synchronizes itself which minimizes the error rate and optimizes reliability. The binary command is multiplied with a rectangular pulse to generate a binary data waveform d(t).

The d(t) waveform goes through encryption for reliable point to point communication. The waveform undergoes BFSK modulation[17]. The modulated wave maintains phase continuity at all transition points and even at those points of time where the incoming binary data stream switch back and forth between symbols 0 and 1.The BFSK signal output spectrum can be seen in Fig. 5.

The BFSK signal we get as:

$$BFSK(t) = A\cos\{\omega_o t + (d(t).\Omega.t)\}$$
$$= A\cos\{(\omega_o + (d(t).\Omega)t)\} \qquad (11)$$

here,

ω_0 is the carrier frequency

$$\Omega = \frac{1}{2}|\omega_H - \omega_L| \qquad (12)$$

When bit 1 is transmitted, d(t) = +1 and,

$$\omega_H = \omega_0 + \Omega \qquad (13)$$

When bit 0 is transmitted, d(t) = -1 and,

$$\omega_L = \omega_0 + \Omega \qquad (14)$$

The BFSK output is then FM modulated and the generated FM modulated signal is:

$$FM(t) = A_c\cos\{\omega_c t + 2\pi K_f \int m(t)dt\} \qquad (15)$$

At the time of reception, the signal received goes through the pre-amplifier section (Fig. 6). It amplifies the received low power signal without significantly degrading its SNR. The FM signal is then demodulated using a differentiator. The resultant signal is both amplitude and frequency modulated which is given by S(t).

$$S(t) = A_c\{\omega_c + K_f m(t)\}\sin\{\omega_c t + K_f \int m(t)dt\} \qquad (16)$$

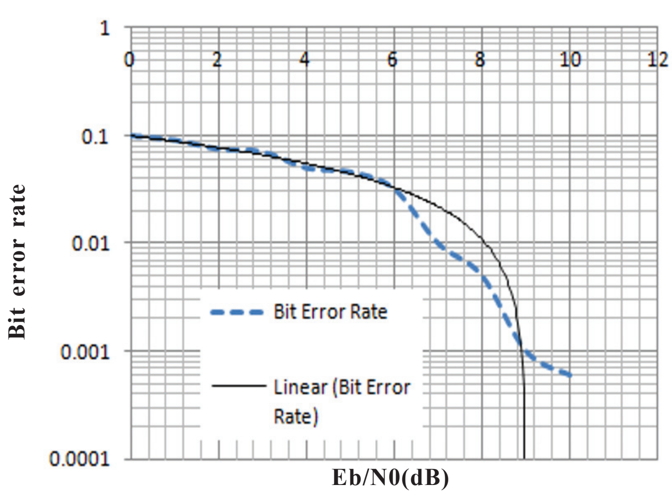

Figure 7. Plot between BER and E_B/N_0.

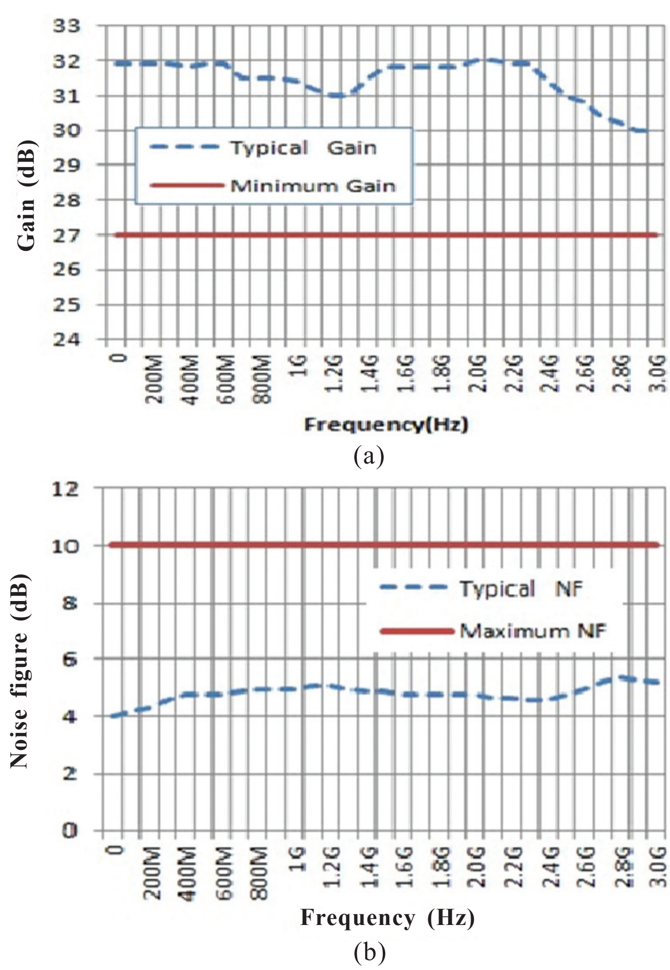

Figure 8. (a) Gain measurement, (b) Noise Figure measurement.

m(t) can be recovered by envelope detection method. By using square law detection method, BFSK signal is recovered. Then the signal goes through proper decryption and decoding for recovering the original command frame.

The performance of the code based system is done by checking the bit error rate (BER) performance (Fig. 7).

Encryption technique in this system makes one to one communication safe and secure. Instead of choosing tones, command codes can be changed easily.

It is capable of controlling one vehicle at a time. By using combiner[18], the system is capable of controlling 2 vehicles but there will be an inter modulation distortion and the range coverage will decrease per system. To support control of multiple vehicles at a time, Code Division Multiple Access (CDMA) technique comes into part.

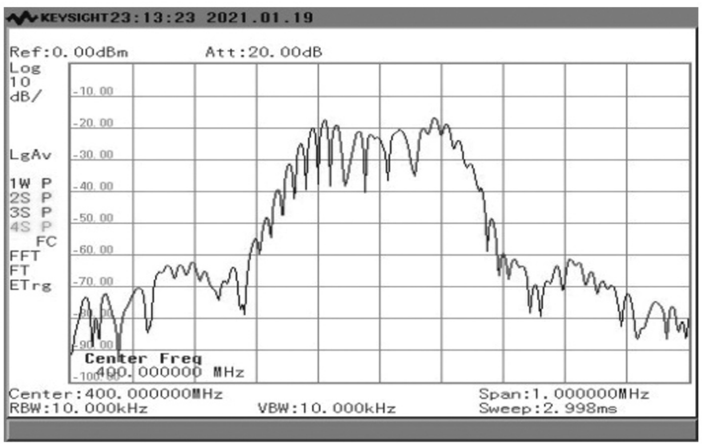

Figure 9. RF Spectrum observed in spectrum analyser for frequency 400 MHz.

4.3 CDMA Based System

CDMA technique in FTS is capable of controlling multiple flight vehicles at a time. In CDMA[19], an entire bandwidth is being used by the user all the time and each has its unique codes (PN codes) to recover the data[20]. The system is based on spread spectrum concept[21-22]. The transmitter has encoded message signals which are spread using 1023 gold codes. The gold codes are generated using two maximal length sequences and shift registers. The spread data are then modulated using locally generated carrier having different phase offsets for each channel. The modulated signals are summed up and fed to a DAC. The output is then filtered out and fed to a converter module. Here the signal is up converted. After that the signal is amplified and transmitted through the antenna as shown in Fig. 10. A whip antenna will be used for receiving the signal locally.

The signal is fed to a down converter module. In this the signals pass through stages of BPF, amplifier and IF sections. After that the resultant IF signals are digitized using an ADC. The digital signals are then down converted using a local carrier to get the base band signal. The base band signal is fetched to a matched filter to acquire and track the incoming signal. A decoder module decodes the data and the corresponding data for RSP is generated and displayed in the channel as shown in Fig. 11.

In CDMA, signal to be transmitted is dispersed across a wide bandwidth. So it is robust to noisy and fading environment. It is a secure technique as transmitted information is below noise floor and it also uses the entire bandwidth simultaneously[23]. The channel power measured is shown in Fig. 12.

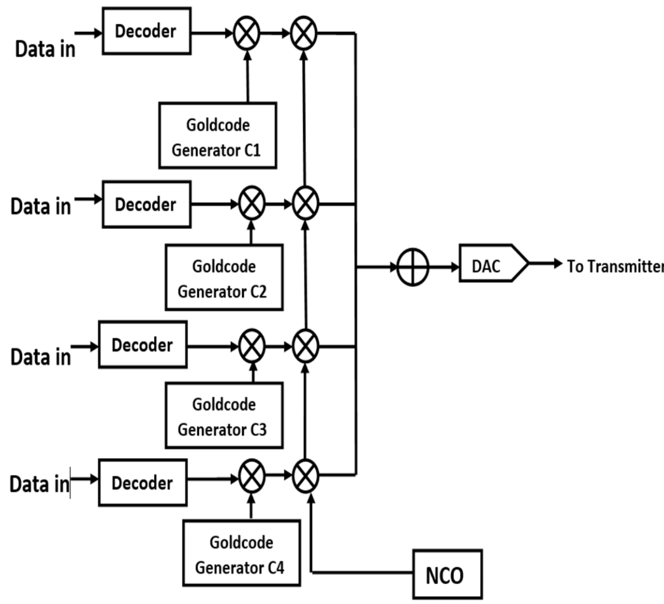

Figure 10. Base band transmitter block diagram for CDMA system.

Orthogonal codes have been used in CDMA. Here orthogonality needs to be maintained in order to recover the original data. Self jamming is observed in CDMA due to loss of orthogonality of PN codes or spreading sequence of different users. It doesn't require any synchronization. Due to code word allocation, interference is reduced. In CDMA, time synchronization is always required for link robustness.

4.4 Enhanced Flight Termination System

Enhanced Flight Termination System (EFTS)[24-25] started for the development of next generation flight termination system. The objective was to investigate more robust command links for flight termination including message format and modulation techniques. An EFTS feasibility study was initiated in April 2000 and continued for 2 years. The EFTS Flight Termination Receiver (FTR) design started in 2004 while the ground equipment development started in 2005.

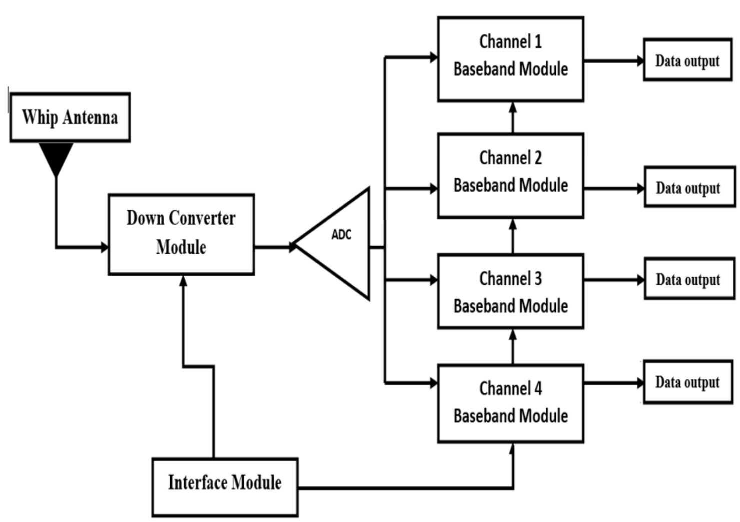

Figure 11. Local receiver block diagram for CDMA system.

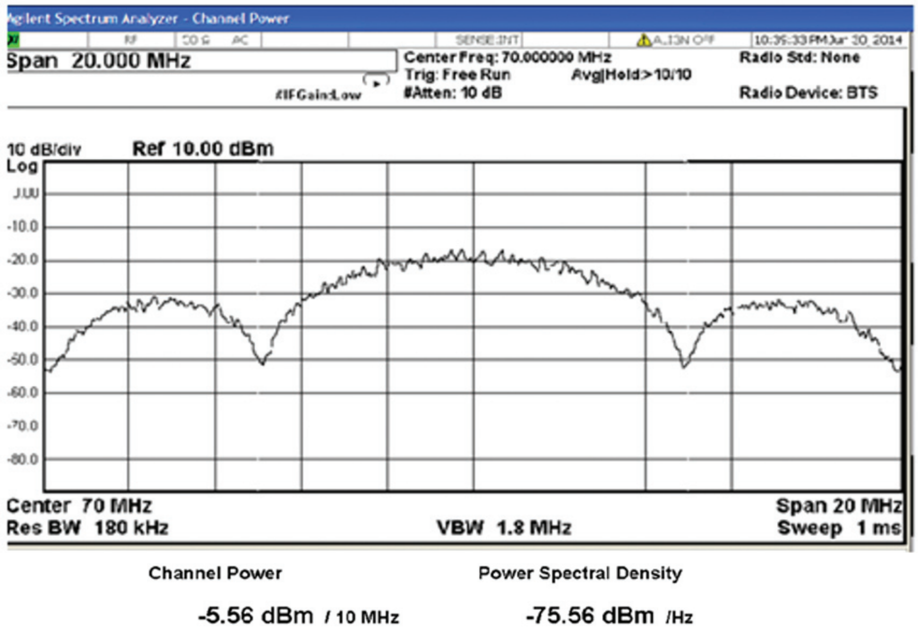

Figure 12. Channel power for CDMA system.

Table I. Advantages and disadvantages of different approaches of modulation schemes used in EFTS

Modulation schemes	Advantages	Disadvantages
BFSK Approach	Tolerant of phase noise, Adapts easily to 3-DES and AES, Multiple receivers can receive & check channel simultaneously with only synchronization word and a pilot bit.	Requires bit/frame synchronisation, Doesn't improve anti-jam capability, Use of hamming code doesn't provide adequate error protection, Use of hamming code doesn't provide adequate error protection.
Bi-Phase level CPFSK Technique	Has a strong CRC Code, Tolerant of phase noise, shows good BW and improved SNR, Can address multiple vehicles in a single frame, Adapts easily to 3-DES and AES but AES is more efficient, Robust against signal degradation.	The proposed 256-bit AES security method is not approved, Long frame length can lead to potential problems in noisy and RF environment as a result entire packet can be rejected by one-bit error.
Enhanced secure flight termination system	Uses non-coherent modulation which is robust to interference, Tolerant of phase noise, Has a good BW and SNR, Requires shorter implementation time	Prone to interference and does not improve anti-jam capability, Uses NRZ which has low bit rate applications, 3-DES has a lot of overhead compared to AES, Security proposal uses recommended counter field.
Enhanced High Alphabet Non-coherent 3 of 13 Tone messaging	Uses modulation technique with low risk and is compatible, It is insensitive to short bursts of interference, Adapts to only 3-DES encryption method, Tolerant of phase noise, The long tone character is tolerant to radar and other short duration pulse interference, Ground system is addressed in depth.	Ground stations have to be time multiplexed, The scheme does not improve anti-jam capability, Base band analogue approaches are not forward thinking, Incorporating AES is problematic as they can decrease update rate, Incorporating AES is problematic as they can decrease update rate, Use of hamming code does not provide adequate error protection, There is a possible loss in competitive marketing, There is a possible loss in competitive marketing, No proper analysis of receiver BER performance, No arrangement to address multiple receivers.
Pseudo-random Code	Has limited CW anti-jamming characteristics, It can command 8 vehicles from a single transmitter, It uses multiple command transmitters to provide higher link It uses multiple command transmitters to provide higher link availability and better support for multiple range and long distance missions, Coherent detection results in increased link margin, Provides long delay multipath protection.	Technology is unproven and riskier to implement, Provides no multi path mitigation for short delay multi path, Provides no multi path mitigation for short delay multi path, It is susceptible to phase noise because of coherent detection, Unsure of vehicle phase antenna patterns, Security approach is not well defined, Analysis is required for complex power control system.
Scalable 3-DES Encrypted BPSK Modulation	Frame format is versatile, efficient with high message rate, Increased link margin because of coherent detection, Uses 3-DES security technique, 12 vehicles can be addressed with one message	BPSK is prone to co-channel interference; BPSK requires carrier phase synchronization which can increase acquisition time, acquisition time, and The vehicle phase antennas can degrade phase modulation.

The entire development process was completed in 2007 following which the range testing started in July 2007. The EFTS system provides user control for telemetry power adjustments. It is field programmable so it increases system availability time. Its data link has a FTR addressing space over RCC (Range Commanders Council) complaint IRIG systems[26], resulting in the ability to communicate with more vehicles per mission than the current IRIG system. It provides additional security over inadvertent activation.

The entire EFTS study program was divided into 4 phases: Requirement definition/Range infrastructure, Technology Assessment, Technology Demonstration and RCC standard. The overall development process needs to follow the RCC standard for following protocols, security and range validation. The evaluation includes security, selectable termination for multiple operations, use of existing RF spectrum, impact on existing ground and airborne equipment, impact on termination and processing, maturity and reliability of technology and cost.

The RSO generated commands are sent through the reception system to a remote transmitting station and then to the flight vehicle[27]. The transmitting data are also monitored at the transmitting end. They are then decoded, checked for accuracy and relayed back for confirmation.

The Central Command Monitoring System (CCRS) can work in both manned and unmanned mode. The command station process group accepts carrier, command and system control request from the CCRS. It processes the request, checks the errors and initiates a proper action. The modulation group is responsible for encoding the audio tones and forming the command message. RF transmitting group is responsible for transmission of modulated message via exciter, power amplifier and antennas.

In the technology assessment, the flight termination link, modulation schemes and message format are decided. For choosing a modulation scheme out of the various approaches, the phase noise, bit error rate, inter modulation, gain balance and linearity measurements are taken into consideration. The different approaches with their advantages and disadvantages are presented in Table 1.

Considering the security, PN code has advantages over others as it has inherent anti-jamming properties but it is very expensive. The aim of the study is to use a system which is both secure and cost effective. The selected scheme needs to have a matured technology with less cost, reliable low bit rate, high phase noise, min bandwidth requirement and proper link availability. BPSK, modified high alphabet and CPFSK[28] (Continuous Phase frequency Shift Keying) can control single system whereas CDMA offers multiple access method and anti-jamming capability.

In technology demonstration, the modelling and simulation process are conducted. Based on the study, it is observed that CPFSK and Modified High Alphabet MHA) schemes are optimal modulation schemes for EFTS. CPFSK is easier to support and upgradable based on sensitivity, technical demonstration and test equipment availability.

The last phase of the EFTS study provides the RCC standard recommendation which finalizes the overall process by developing the request and proposing package for design validation.

4.5 Autonomous Flight Termination System

To overcome traditional human in loop FTS systems, National Aeronautics and Space Administration (NASA)[29-30] has designed an Autonomous Flight Termination System (AFTS) which is an independent self-contained subsystem mounted on a launch vehicle.

AFTS decisions depend on Global Positioning System (GPS)[31] and Inertial Navigation System (INS) sensor data. It reduces the ground based mission flight control personnel, gives global coverage; increases launch responsiveness and can support multiple vehicles simultaneously. Even though the system is autonomous, jobs like launch clearance, mishap announcement and investigation, post flight data reviews still require human involvement. The main concern in this course of action is the safety precaution. With faster computational speed, computers can get the information from the onboard package, predict the impact zone and evaluate the information accordingly to ensure safety.

AFSS (Autonomous Flight Safety System) brought out the vehicle navigation data from the onboard sensors and made the software based decisions according to a certain rule set. NASA worked with range safety community to calculate system level function, design, and test and maintenance requirements according to the AFTS aspects. Some of the primary features of AFTS include redundancy, good reliability, complete functional independence, single point tolerance, flexibility according to requirement and built in capability to issue telemetry. The architecture of AFTS requires subsystem redundancy. The goal is to build a system having all the functional requirements.

The system is connected to multiple navigation sensors. The sensor unit consists of GPS and Inertial Measurement Unit (IMU). To provide redundancy, each sensor is interfaced with each of the Flight Processor (FP). Sensor data are validated using checksum, self monitoring status indicators, by verification of sensor data latency and performing reality checks. Each processor is individually interfaced with Command Switch Logic and Interlock Circuit (CSLIC) which provide power and data interfacing among components. It also permits automatic launch abort if any subsystem experiences a fault prior to launch. This unit provides a means for arming and disarming the FTS safe/arm units for both ground and flight operations. The various commands are issued like MON (Monitor), RTL (Ready to Launch), ARM, FIRE during flight operations for performing specific activities.

NASA developed wrapper interface software and a Core Autonomous Safety Software (CASS) running on a COTS processor which is the interface between all the sensors and the AFTS hardware. AFTS provides responsive access to space at a reduced cost. NASA's AFTS has undergone hardware development and flight certification and has completed ground test qualification for operational use.

5. OUTCOMES

After the survey on various methodologies, comparison table is presented in Table 2 summarizing the features and techniques of different flight termination systems. Tone-based system is a well-established method due to its simpler circuit design and it has given a profound result for a long time. The performance of tone-based, code-based and CDMA systems are analysed. Advanced FTS study like EFTS and AFTS

Table 2. Comparison among features of various FTS technologies

Parameters	Tone based	Code based	CDMA	EFTS	AFTS
Modulation Techniques	FM	BFSK+FM	Spread spectrum	CPFSK	-
Encoding Techniques	-	Manchester Encoding	PN Code	CRC Code	-
System complexity	Low	Medium	High	High	High
No. of Controlling vehicles	1	1, 2(using Power Combiner)	Multiple	Multiple	Multiple
Advantages	Simpler design circuitry, Link robustness, Good capture ratio	Encryption codes can be changed easily	Multiple vehicles at a time are used, It has most note worthy Range effectiveness	Has a strong CRC, Tolerant to phase noise, Good BW, Improved SNR	GPS, Auto pilot, Timing Source and decision logic, Multiple vehicle control
Disadvantages	No encryption or error correction mechanism	IMD cannot support multiple vehicles	Near far problem, self-jamming, Time synchronization is required	Long frame length, System complexity	More software dependant, Higher system complexity, Longer frame length

conducted by NASA are studied and analysed. It is seen that AFTS system is the superior one among all other systems on account of GPS, Auto pilot, multiple vehicle control, Global Coverage, more launch responsiveness. The scale of the survey shows an increase in system complexity. It is understood that software involvement with the hardware is increasing day by day and more powerful and reliable software is required for crucial decision making.

6. CONCLUSION

This article gives a brief discussion on requirement and features of FTS and different technologies used in the domain. Single fault tolerance, system impedance, sensitivity, proper channel bandwidth and out of band rejection are some of the key parameters of FTS. To ensure flight safety, all the components of flight vehicle should be installed according to the qualified FTS design. FTS components must satisfy all performance satisfactions during transportation, storage, pre-flight processing and testing. We hope that this article will act as a valuable resource for understanding the current research contributions of flight termination system technologies and hopefully encourage further research efforts to design the next generation FTS systems by proposing better competitive methods to solve system complexity and have a faster interaction. The revolution in artificial intelligence and machine learning technology could provide a gateway to make a better and even more powerful flight termination system.

Motivation for writing this paper is to find out the most reliable technology after a detailed study and comparison of present technologies.

REFERENCES

1. Gourab, M.K.; Priyadarshini, S.; Roy, A. & Mandal, U. Automatic change over unit for flight termination system. *In* 2nd International Conference on Range Technology (ICORT), 2021, pp. 1-6. doi: 10.1109/ICORT52730.2021.9582071.
2. Panda, A.R.; Mishra, D. & Ratha, H.K. Implementation of SCADA/HMI system for real-time controlling and performance monitoring of SDR based flight termination system. *J. Ind. Inf. Integr.*, 2016, **3**, 20-30. doi: 10.1016/j.jii.2016.07.001
3. Lopez, N.D.; MacDonald, M.E. & Abouzahra, M.D. LSSC Solid-state high-power amplifiers. 19th European Radar Conference (EuRAD). IEEE, 2022. doi:10.23919/EuRAD54643.2022.9924904
4. Kovalev, I.; Kovalev, D.; Testoyedov, N.; Borovinskii, D. & Golovenkin, E. Prototyping for communication, navigation and power supply subsystems of on-board equipment of unmanned aerial vehicles. *In* AIP Conf. Proc., 2021, **2402**(1), 020058. doi:10.1063/5.0071312
5. Tabassum, A. & Bai, H. Dynamic control allocation between onboard and delayed remote control for unmanned aircraft system detect-and-avoid. *Aerosp. Sci. Technol.*, 2022, **121**, 107323. doi:10.1016/j.ast.2021.107323
6. Elsayed, M.; Reda, M.; Mashaly, A.S. & Amein, A.S. Review on real-time drone detection based on visual band Electro-Optical (EO) sensor. *In* 2021 Tenth International Conference on Intelligent Computing and Information Systems (ICICIS), 2021, 57-65. doi:10.1109/ICICIS52592.2021.9694151
7. Zhang, J.A.; Liu, F.; Masouros, C.; Heath, R.W.; Feng, Z.; Zheng, L. & Petropulu, A. An overview of signal processing techniques for joint communication and radar sensing. *IEEE J. Sel. Top. Signal Process.*, 2021, **15**(6), 1295-1315. doi:10.1109/JSTSP.2021.3113120
8. Mikhailik, D.A.; Kozlov, Y.V. & Malygin, I.V. Design and study of an antenna system for receiving telemetry information from spacecraft cubesat. *In* 2022 Systems of Signals Generating and Processing in the Field of on Board Communications*,* 2022*,* 1-5. doi:10.1109/IEEECONF53456.2022.9744257
9. Pan, L.; Xu, D.; Zhang, J.; Yin, C.; Wu, Z. & Guo, Y. Active noise cancellation frequency-locked loop with

a notch filter. *Power Electron. Technol.*, 2021, **21***(12)*, 1743-1756.
doi:10.1007/s43236-021-00310-z

10. Mohamed, R.O.E.; Mohamed, S.M.A. & Abashar, H.A.E. Unmanned aerial vehicle intelligent ambulance based system. *In* 2020 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE), 2021,
doi:10.1109/ICCCEEE49695.2021.9429646
11. Bernhardt, M.; Marin, J. & Riihonen, T. Estimation of receiver frequency deviations in multifunction frequency-modulating transceivers. *In* 2022 IEEE 95th Vehicular Technology Conference:(VTC2022-Spring), 2022, 1-5.
doi:10.1109/VTC2022 -Spring54318.2022.9860468
12. Cirjulina, D.; Pikulins, D.; Babajans, R.; Zeltins, M.; Kolosovs, D. & Litvinenko, A. Experimental Study on FM-CSK Communication System for WSN. *Electronics*, 2022, **11**(10), 1517.
doi:10.3390/electronics11101517
13. Wang, D.; Wang, G.; Lu, D.; Yang, N. & Zhang, Q. Design of wideband base station antenna by involving fragment-type structures on dipole arms. *IEEE Trans. Antennas Propag.*, 2022, **70**(7), 5953-5958.
doi:10.1109/TAP.2022.3161285
14. Panda, A.R.; Mishra, D. & Ratha, H.K. FPGA implementation of a tone-based flight termination system in a software-defined radio platform. *IEEE Trans. Industr. Inf.*, 2017, **13**(5), 2360–2368.
doi:10.1109/TII.2017.2709344
15. Hu, X.; Peng, S.; Guo, B. & Xu, P. Accurate AM-FM signal demodulation and separation using nonparametric regularization method. *Signal Process.*, 2021, **186**, 108131.
doi : 10.1016/j.sigpro.2021.108131
16. Panda, A.R.; Mishra, D. & Ratha, H.K. Fpga implementation of software defined radio-based flight termination system. *IEEE Trans. Industr. Inform.,* 2014*,* **11**(1), 74-82.
doi:10.1109/TII.2014.2364557
17. Hu, H.; Yu, G.; Li, Y.; Qiu, Y.; Zhu, H.; Zhu, M. & Zhou, H. Design of a radial vortex-based spin-torque nano-oscillator in a strain-mediated multiferroic nanostructure for BFSK/BASK applications. *Micromachines*, 2022, **13**(7), 1056.
doi: 10.3390/mi13071056.
18. Varlamov, O.V.; Nguyen, D.C. & Grychkin, S.E. Simultaneous application of several synthetic methods for high efficiency radiofrequency amplification. *In* 2021 Systems of Signals Generating and Processing in the Field of on Board Communications, 2021, pp. 1-5
doi:10.1109/IEEECONF51389.2021.9416126
19. Kebede, T.; Wondie, Y.; Steinbrunn, J.; Belay, H. & Kornegay, K. Multi-carrier waveforms and multiple access strategies in wireless networks: Performance, applications and challenges. *IEEE Access*., 2022, **10**, 21120-21140.
doi:10.1109/ACCESS.2022.3151360
20. Rezai, M. & Salehi, J.A. Quantum CDMA communication systems. *IEEE Trans. Inf. Theory,* 2021, **67**(8), 5526-5547.
doi:10.1109/TIT.2021.3087959
21. Xiang, C.; Tang, C. & Ding, C. Shortened linear codes from APN and PN functions. *IEEE Trans. Inf. Theory*, 2022, **68**(6), 3780-3795.
doi:10.1109/TIT.2022.3145519
22. Haab, D.B.; Moradi, H. & Farhang-Boroujeny, B. Spread spectrum symbol detection with blind interference suppression in FBMC-SS. *IEEE open J. Commun. Soc.,* 2021*,* **2**, 1630-1646.
doi:10.1109/OJCOMS.2021.3090356
23. Morsy, M.A. & Alsayyar, A.S. Performance analysis of OCDMA wireless communication system based on double length modified prime code for security improvement. *IET Commun.,* 2020, **14**(7), 1139-1146.
doi:10.1049/iet-com.2019.0533.
24. Arce, D.; Garza, R. & McAndrews, T. Enhanced flight termination system study-Phase II and III status. *IFT*. 2001, http://hdl.handle.net/10150/606407
(Accessed on 09 October 2018).
25. Ancel, E.; Young, S.D.; Quach, C.C.; Haq, R.F.; Darafsheh, K.; Smalling, K.M. & Johnson, T.A. Design and testing of an approach to automated in-flight safety risk management for sUAS operations. *In* Aiaa Aviation, 2022, 3459.
doi:10.2514/6.2022-3459
26. Bibhorr, B. & Anand, C.R. Supplemented thrust reversal contraption for enhanced flight termination system (EFTS). *In* 2021 2nd International Conference on Range Technology (ICORT)*,* 2021, 1-5.
doi:10.1109/ICORT52730.2021.9581587
27. Rosales, Ervin A. Design, testing, and development of a redundant flight safety system. *In* 26th AIAA Aerodynamic Decelerator Systems Technology Conference, 2022.
doi:10.2514/6.2022-2727
28. Wang, Y.; Wei, M.D. & Negra, R. System-level performance analysis of high-data-rate frequency-to-amplitude converter based CPFSK Transceiver at 60 GHz. *In* 2021 IEEE Radio and Wireless Symposium (RWS), 2021, pp. 57-59.
doi:10.1109/RWS50353.2021.9360365
29. Schopferer, S.; Donkels, A.; Schirmer, S. & Dauer, J.C.. A multi-disciplinary scenario simulation for low-altitude unmanned air delivery. *In* Automated Low-Altitude Air Delivery: Towards Autonomous Cargo Transportation with Drones, Dauer, J.C. (eds), Research Topics in Aerospace. *Springer, Cham*. 2022, 423-447.
doi:10.1007/978-3-030-83144-8_17
30. Rothe, D. & Nikodem, F. System architectures and its development efforts based on different risk classifications. In Automated Low-Altitude Air Delivery: Towards Autonomous Cargo Transportation with Drones, Dauer, J.C. (eds), Research Topics in Aerospace. *Springer, Cham.* 263-288.
doi:10.1007/978-3-030-83144-8_11
31. Mattei, A.L.P.; Orbital, E.S.A.; Toledo, C.F.M.; da Silva Arantes, J. & Trindade Jr., O. Unmanned aerial vehicles flight safety improvement using in-flight awareness. *Intell. Inf. Manag.*, 2021, **13**(2),97-123.
doi:10.4236/iim.2021.132005

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