A SYNCHRONOUS REAL TIME NETWORK BASED WIRELESS AIRBORNE DATA ACQUISTION SYSTEM

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ABSTRACT

The purpose of this paper is to present a chronology from a Small Business Innovation Research Program (SBIR) showing the impact of a wireless network architecture on future airborne data acquisition systems. The major advantages and challenges associated with the use of wireless network data acquisition versus wired time division multiplexing systems are rooted in data latency, bandwidth efficient data transmission while maintaining a low bit error rate and not interfering with existing avionics. Many of the issues raised are subtle and complex. It is not the intent of this paper to give these issues the thorough academic and technical analysis they deserve. It is the hope of the authors that this paper will generate awareness and discussion on these issues.

KEY WORDS

Wireless, network, instrumentation, bandwidth, data acquisition, Direct Sequence Spread Spectrum

INTRODUCTION

Test and Evaluation of military airborne vehicles requires wireless data acquisition systems to augment the current wired systems in use. Currently, wire conductors are routed throughout the aircraft in order to provide a path from each sensor to the host data acquisition system. The wireless requirement originates from:

1) Measurements that are currently impossible or impractical to wire such as those from rotor hubs, penetration of critical structural members such as bulkheads, passage through sealed and high temperature engine areas.

2) Lower the cost of flight testing by reducing the time for the installation, augmentation and removal of the wiring required for the data acquisition system.

The goal of the SBIR was to develop a robust wireless network based data acquisition system suitable for aircraft instrumentation purposes to augment/replace wired systems where needed. Issues such as real time data acquisition, maximum bandwidth utilization, minimal data latency and preventing Radio Frequency (RF) interference with existing avionics were researched.

SBIR PHASE I BACKGROUND AND SELECTION

The Naval Air Warfare Center Aircraft Division (NAWCAD) initiated a Small Business Innovation Research (SBIR) Program for a Wireless Airborne Instrumentation System (WAIS). The primary motive for this effort was to develop a aircraft wireless data acquisition system to acquire data which is currently impossible or impractical to wire such as those from rotor hubs, penetration of critical structural members such as bulkheads and passage through sealed and high temperature engine areas. Response to this effort resulted in 26 SBIR proposals being submitted for evaluation. Of the submitted proposals, two were considered viable to satisfy the requirements. One proposal utilized Radio Frequency (RF) Direct Sequence Spread Spectrum (DSSS) technology and the second proposal utilized Laser (optical) technology. Both wireless technologies appeared technically feasible to operate in the aircraft flight test environment.

The Spread Spectrum (SS) technology resists intentional and non-intentional RF interference, has high immunity to multipath interference, and can share the same frequency band (overlay) with other systems. In particular, SS technology spreads out the original signal frequency spectrum resulting in a much lower power spectral density (PSD) for a given transmitted power. This low signal PSD will appear as broadband Gaussian noise (at the expense of an increased noise floor) to any host aircraft narrowband receiving systems. Since the receivers already contain front-end noise rejecting filters, the SS transmissions should "look like" noise and thereby be ignored resulting in very low interference. DSSS Phase I system specifics included an overall bit rate capability of 121,000 bits/second with a bit error rate (BER) of 1 e-05 at a receiver sensitivity of –90 dBm.

The Laser technology operates in the optical region (above RF) of the electromagnetic spectrum. Consequently, the host aircraft transmitting/receiving systems operating in the RF region should have little EMI interference introduced by the Laser technology. Also, the higher optical frequency permits the use of smaller devices. In addition, because of the extremely low-power 1-milliwatt laser required, battery operation is easily accomplished through small wristwatch size batteries. Laser Phase I system specifics included an overall bit rate capability of 12,000 bits/second with a BER of 1 e-05.

In addition to the technical merits of these two proposals, these efforts were unique in that both contractors agreed to provide working "breadboard" models of their systems under the terms of the Phase I contract. The intention was to provide test data from both approaches as a basis for determining if either of the systems were worth pursuing further through a SBIR Phase II contract. Consequently, both contractors produced a wireless system (using their proposed technology) capable of transmitting and reproducing one signal with a frequency response up to 100 HZ. By reproducing the signal to its original form, the test results could be directly compared to a pair of wires acting as truth data. In doing this, the systems can be modeled as "wireless signal conduits" with an end to end accuracy stating the ±% error introduced by the systems.

The Phase I demonstration results showed that both DSSS and Laser wireless data systems were able to transmit and reproduce the analog signals. The spread spectrum system tests were performed on a T-2 aircraft inside an aircraft hangar with the transmitter located in the wingtip and the receiver located in the fuselage. The Laser system required direct line of sight between the transmitter and the reflector. Operationally, this is typically implemented by replacing two rivets in the airframe with the transmitter and receiver. Since the intent was just proof of concept, the Laser system tests were performed using a bench setup inside the hangar. The Laser system became degraded by direct sunlight "washing out" the wireless link thereby causing data dropouts. The contractor felt the use of a higher power pulsed laser system or narrow band-pass optical filters would provide a solution for the system to work in direct sunlight. In addition, alignment of the transmitter and receiver can be difficult because of the low power and small beam width. As such, the demonstrated Laser system needed more refinement before it could be considered as a robust wireless data link suitable for the aircraft flight text environment. The DSSS system in conjunction with its low power 0.35-watt transmitter was able to transmit data from the wingtip through the aircraft superstructure and be reproduced in the fuselage with the aircraft outer compartment doors closed, thereby forcing the data to be reproduced from the labyrinth path inside the aircraft. Consequently, the RF DSSS approach was selected and approved for Phase II SBIR funding (up to 750,000 dollars).

Detailed requirements concerning extreme environmental conditions, EMI and other factors constituting full flight-worthy airborne equipment were relegated to the Phase II effort. System enhancements such as higher data rates, multiple channels and applications oriented issues such as input data signal types were also relegated.

SBIR PHASE II WAIS IMPLEMENTATION

The WAIS architecture is modeled as an airborne distributed data acquisition system consisting of a controller called a Central Data Collection Unit (CDCU) and multiple Remote Data Gathering Units (RDGUs). Similar to wired distributed systems, the RDGUs are placed close to groups of signals in order to minimize the amount of wire spanning the distance to individual transducers while the CDCU is located in a centralized area. Each RDGU is able transmit its data to the CDCU, which then reformats the data in preparation for telemetry and onboard recording. The network setup is performed by a Windows® Graphical User Interface (GUI) on a Personal Computer (PC) and downloaded to the controller via the RS-232 port. Figure 1 shows the final configuration of the WAIS network. The decisions made leading to the final configuration are discussed throughout this paper.

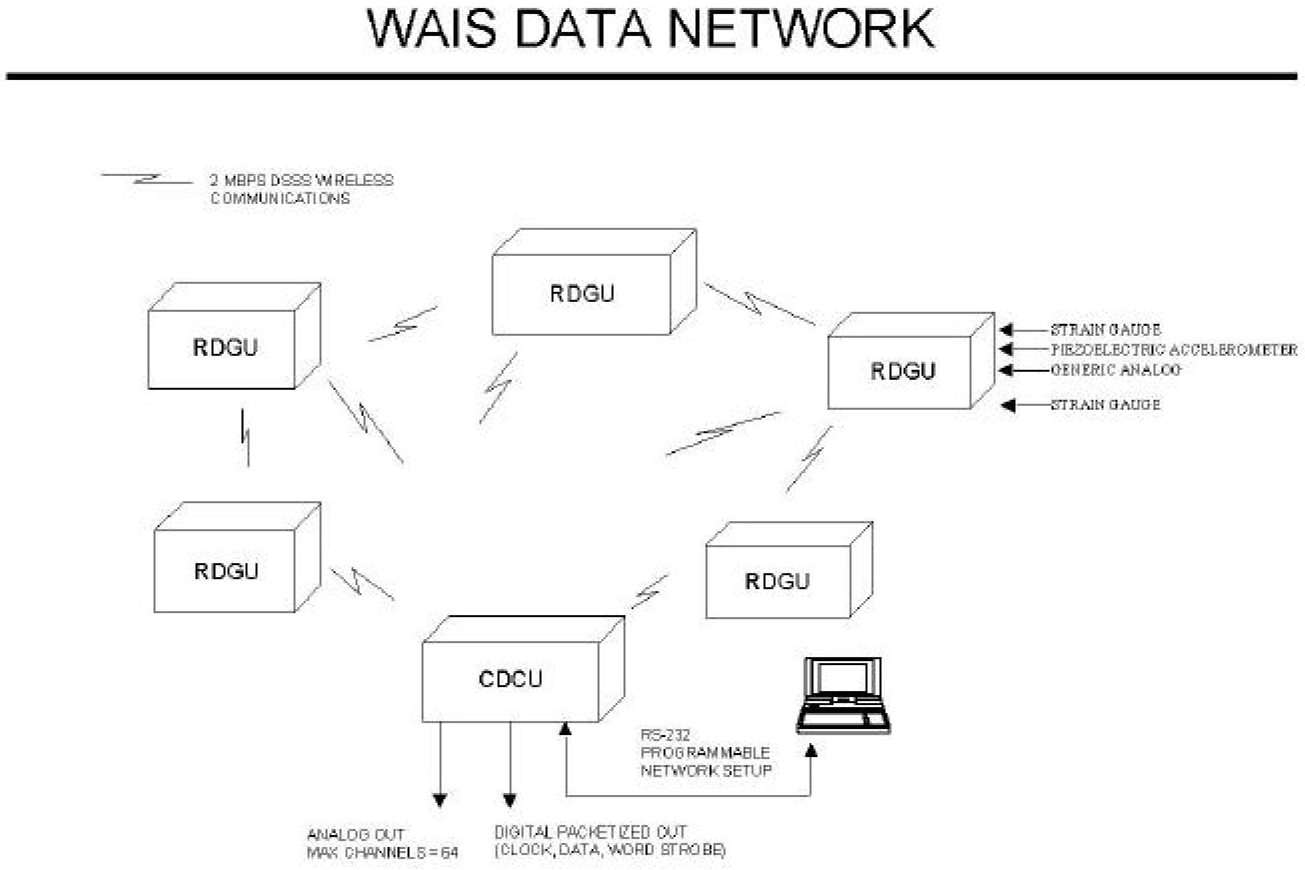

Figure 1, WAIS Data Network (final configuration)

The project goals emphasized developing a robust wireless network-based aircraft data acquisition system designed to augment or replace existing wired systems. The system's input capabilities were also tailored for specific measurements that favored wireless data acquisition over traditional wired techniques. The project sought to minimize duplication of effort, and to build upon the success of other wired systems such as the Common Airborne Instrumentation System (CAIS) and the Advanced Airborne Test Instrumentation System (AATIS). Consequently, the project investigated the development of a distributed wireless airborne data acquisition system capable of the following applications: 1) Continuation of Phase 1 efforts, including the transmission and reproduction of analog signals with multiple channels, greater accuracy, higher sample rates, and smaller units; 2) Internal battery operation, making the system truly wireless; 3) Composite digital output from the controller consisting of both IRIG PCM and a packetized data format for export to a PC. In order to meet these goals, an assessment of state of the art wireless communication systems was necessary.

In communications theory, available bandwidth is typically the boundary that leads to the maximum transmitted data rate capacity of a channel. Due to the multiple channel requirements, data throughput naturally became the driving force behind the entire network design. Therefore, the 121,000 bits/second radio used for Phase I was not selected in Phase II due to its inability to satisfy the aggregate data requirements. Consequently, an evaluation was performed to determine the best wireless technology system. The Federal Communications Commission (FCC) has allocated three unlicensed Industrial Scientific Medical (ISM) frequency bands suitable for Wireless Local Area Network (WLAN) transmissions: 902 to 928 MHz (BW= 26 MHz), 2.4 to 2.485 GHz (BW = 85 MHz), and 5.725 to 5.85 GHz (BW = 125 MHz). The most desirable system would utilize the frequency band with the highest bandwidth, and be designed from the ground up with a topology that could take full advantage of that bandwidth. However, due to SBIR Phase II funding and schedule limitations, the radio system development had to be minimized. The project surveyed various, low cost Commercial Off The Shelf (COTS) systems that were currently available to meet the requirements of the network.

The unlicensed frequency bands mentioned above are still regulated by the FCC. Within these allocated frequency bands, Narrowband and SS wireless systems are the most common. Narrowband channels are used every day by millions of cellular phone customers. In the ISM bands however, narrowband RF power output is required to be less than 0 dBm. This restriction is intended to reduce interference between the variety of commercial and industrial products present in these bands. However, low RF output power relates directly to degradation in BER performance and a decrease in range.

SS systems represent a more novel approach to reducing interference among devices in the same frequency space. These systems employ methods that spread their average transmitted power across the band of interest, and therefore are allowed to transmit at 30 dBm of RF output power. Frequency Hopping Spread Spectrum (FHSS) systems achieve a lower time averaged PSD by jumping from one narrowband frequency to another in a predefined manner. Once a transmitter and receiver have locked onto a sequence of jumps, interference and collisions are handled by simply switching to the next frequency and attempting a retransmission. Jumping from one frequency to another, over time, contributes to a lower average power level in the band. DSSS systems spread their spectrum in a different way. Baseband data is concatenated (XOR'd) with a Pseudorandom Number (PN) code bit stream operating well above the baseband rate, called the chipping rate. The resulting output stream now carries much more data content, and hence frequency content, than the original baseband signal. This effectively widens the PSD of the RF output and spreads the energy of the data content across the band of interest. The receiver uses wideband filters and downconverts the RF signal back to the chipping rate. This chipped signal is then correlated, removing the PN code from the data, and the original baseband information is then recovered. The length of the PN code is similar to the level of redundancy of the data, and as such, longer PN codes are more robust. The measure of this robustness can be defined as the Processing Gain, and is calculated as 10 log [PN code length (in bits)]. Clearly, a transmitter and receiver must operate at the same chipping rate, and with the same PN code to communicate. The choice of PN codes allows for many simultaneous communication channels in the same frequency space, even by completely disparate systems. PN code length and format create many possibilities for the manipulation of the transmitted waveform.

SS technologies enable performance gains in range and BER performance relative to Narrowband technologies. This led to the following systems being considered for the application: 1) The AT&T 915 MHz DSSS system with a 2 Mbps rate; 2) The Pulse Engineering 2.4 GHz FHSS system with a 1 Mbps rate; 3) The Proxim 2.4 GHz FHSS system with a 1.6 Mbps rate; 4) The Harris Semiconductor 2.4 GHz DSSS system with a 4 Mbps rate. Unfortunately, no proven commercial products existed in the 5.725 to 5.85 GHz band. Even though DSSS was successfully used in Phase I, both FHSS and DSSS techniques were evaluated.

High immunity to RF multipath was identified as a requirement for the RF communication link. Multipath is a type of interference that results when a transmitted signal follows more than one path to the receiver. These signals are phase shifted from one another, and destructively interfere with each other at the receiver's antenna. An example of multipath interference is the disruption of FM radio reception in an automobile using a monopole antenna near tall buildings. For those who have stopped at a traffic light while listening to an FM radio, and noticed that the station is lost momentarily, likely experienced the effects of multipath. A typical installation of the data acquisition system would distribute the RDGUs throughout an airframe structure. The metallic airframe is a relatively confined RF environment, and the probability of multipath is significant, causing received signal degradation between the RDGU's and the CDCU. Therefore, DSSS radios were desired because of their inherent ability to suppress the effects of multipath. By decorrelating the aggregate signal at the receiver, the delayed forms of the original signal due to multipath are rejected. The decorrelation and signal recovery by the processing gain, or de-spreading operation in the receiver, helps to reject the delayed forms of the original signal present at the receiver's front end. The de-spreading operation multiplies the incoming signal by the original spreading waveform. This process correlates the spreading waveform with the incoming signal to collapse the incoming signal into the data bandwidth while the undesired signals remain spread. DSSS also has the ability to significantly reject narrowband interference due to the de-spreading or processing gain of the received signal.

Although FHSS systems could support more nodes per physical area than DSSS systems, the higher interference immunity offered by DSSS allows closer spacing of same channel networks resulting in more networks per frequency band. Consequently, the AT&T and Harris Semiconductor DSSS systems became the most desirable alternatives. The Harris system had the advantage in data rate capabilities but the AT&T system was an established product that offered a complete DSSS transceiver. The Harris system was not yet a mature product offering at the time. The AT&T system also had a simple modem interface, integrated antenna, and ¼ watt output power, and performed in the laboratory with a BER of 1 e-08 at a receiver sensitivity of –75 dBm. In conclusion, the AT&T 915 MHz DSSS 2 Mbps system was chosen because its technology insertion was very low risk thereby conforming to the SBIR Phase II funding/schedule profile.

Systems engineers also discovered that a DSSS transceiver pair could synchronize with less overhead. Because synchronization occurs at the bit rate in the baseband processor, as opposed to the hopping rate for FHSS, we were able to avoid developing additional hardware and software that could tune the RF transceivers after each hop.

CONVENTIONAL AIRCRAFT DIGITAL DATA ACQUISTION SYSTEMS

The Department of Defense (DoD) uses a wide variety of data acquisition systems to provide data in support of the test and evaluation of weapon systems. Typically, these are synchronous time division multiplexed (TDM) systems distributed throughout the test article. Numerous factors that are taken for granted in traditional TDM systems (such as time correlation, simultaneous sampling, constant latency, extremely low probability of lost data, etc.) become challenges when the use of data acquisition networks (wireline or wireless) are used. In general, TDM systems are synchronous and provide continuous time determinant acquisition and delivery of data. Each data word and its time relationship to other words in the TDM stream are clearly defined. TDM data has a constant latency with a very high (almost certain) probability of delivery. Constant latency can be compensated for in data processing algorithms.

CONVENTIONAL NETWORK DATA ACQUISTION SYSTEMS

In comparison to TDM data, the time relationship and definition of packetized data within a network is more complex. For example, in some systems, it is possible for packetized data to be delivered out of order and the data structures within the data packets may be dynamic. Latency management and the associated probability of delivery are another source of challenges facing the use of data acquisition networks. Packetized data, by its very nature, can be bandwidth inefficient. Using identical data sets, packetized data will require more bandwidth than an equivalent TDM stream. For some aircraft data reduction requirements, system wide simultaneous sampling is required for complex algorithms that combine multiple samples into a single derived parameter. Due to the asynchronous nature of traditional networks, system wide simultaneous sampling is a challenge. Commercial networks do not typically operate at the latency or synchronization levels that would be required to satisfy DoD aircraft instrumentation data acquisition requirements.

THE IMPACT OF AIRCRAFT DATA ACQUISITION SYSTEM REQUIREMENTS ON NETWORK ARCHITECTURE

At this point we had to insure the network based wireless system satisfied the original intentions of the SBIR, thereby being a wireless aircraft digital data acquisition system capable of augmenting/replacing wired systems where needed. We realized that some of the paradigms inherit to conventional TDM based aircraft digital data acquisition systems were diametrically opposed to those paradigms employed in networks (wireline or wireless). The impact of this contradiction requires a change in conventional network philosophies when used to satisfy aircraft data acquisition requirements. Consequently, in order to “get the job done”, the two worlds would be blended together to form a practical solution.

A PRACTICAL SOLUTION TO EMPLOYING NETWORK ARCHITECTURE TO AIRCRAFT DATA ACQUISTION

Knowing the requirement was to maintain synchronous data with minimal latency, for both stand-alone operation and to feed current airborne distributed data acquisition systems, the system had to deliver real time, synchronized data with minimal latency out of the CDCU in both analog and digital forms. Two solutions (ideas) were considered to accomplish the requirement. First, the idea was to feed each RDGU with IRIG time and have each word or groups of words (message) time tagged and sent across the DSSS wireless link and have the CDCU reconstruct and output the data. This idea was considered impractical for it requires running wires to each RDGU making the system not so wireless, consumes additional wireless link bandwidth by sending time information and requires more resources inside the CDCU thereby reducing its overall throughput. Instead, *the solution was to synchronize the wireless network*. A simplified explanation of the synchronous real time WAIS network structure is as follows:

A typical wireline or wireless Ethernet network uses a Carrier Sense Multiple Access (CSMA) protocol that allows multiple users to share a communication channel. Specifically for wireless, the IEEE 802.11 standard for communication between fixed or mobile computers is widely accepted and provides a framework for medium access control (MAC) procedures, physical layer (PHY) signaling techniques, privacy procedures, and multiple overlapping networks. The IEEE 802.11 standard which specifies a "carrier sense" before transmit with a subsequent random backoff if carrier is present, could not be used efficiently for WAIS transmissions due to the synchronicity of the transmissions needed to satisfy aircraft data acquisition requirements. In the WAIS system, each RDGU has a fixed amount of data to send to the CDCU per unit time based on the individual channel sample rates. Since multiple data acquisition units can be used, the data is transmitted more efficiently using a Time Division Multiplexed (TDM) scheme to control the "medium access". Efficiency is gained by minimizing the "RF dead time" between the transmissions of data. In the CSMA case, the random backoff could add a significant "RF dead time" between each transmission thereby reducing the overall data throughput.

A Time Division Multiplexed (TDM) scheme is used to transmit data from each RDGU to the CDCU. The data between RDGUs is synchronized to ±300 nanoseconds (ns) and arrives at the CDCU with a 200 millisecond (ms) delay. The Network Real Time Synchronized Mode operates as follows: once every transmit cycle, the CDCU transmits a synchronization pattern which is used by the RDGUs for clock and transmit frame adjustment. Each RDGU is pre-programmed in non-volatile memory to sample each data channel commensurate with its sample rate requirements and transmit the data packets to the CDCU in a prescribed TDM'd fashion to avoid data collisions on the wireless link. This intelligence was put into each RDGU in order to minimize the intervention from the CDCU thereby conserving precious RF bandwidth for the data. The RDGU begins data acquisition and stores the data in circular buffer. When the next synchronization pattern arrives, the RDGU transmits the data at a time determined by the system sample rate parameters. Once received by the CDCU, error checking is implemented to determine if retransmission is necessary. A portion of each transmit cycle is reserved for retransmissions. The total time available for retransmissions depends on the bandwidth or sample rates selected. Available sample rates are 12.2kHz, 6.1kHz, 3.05kHz, 1.5kHz, 763Hz, 381Hz, 190Hz, 95Hz, 47Hz, and 23Hz.

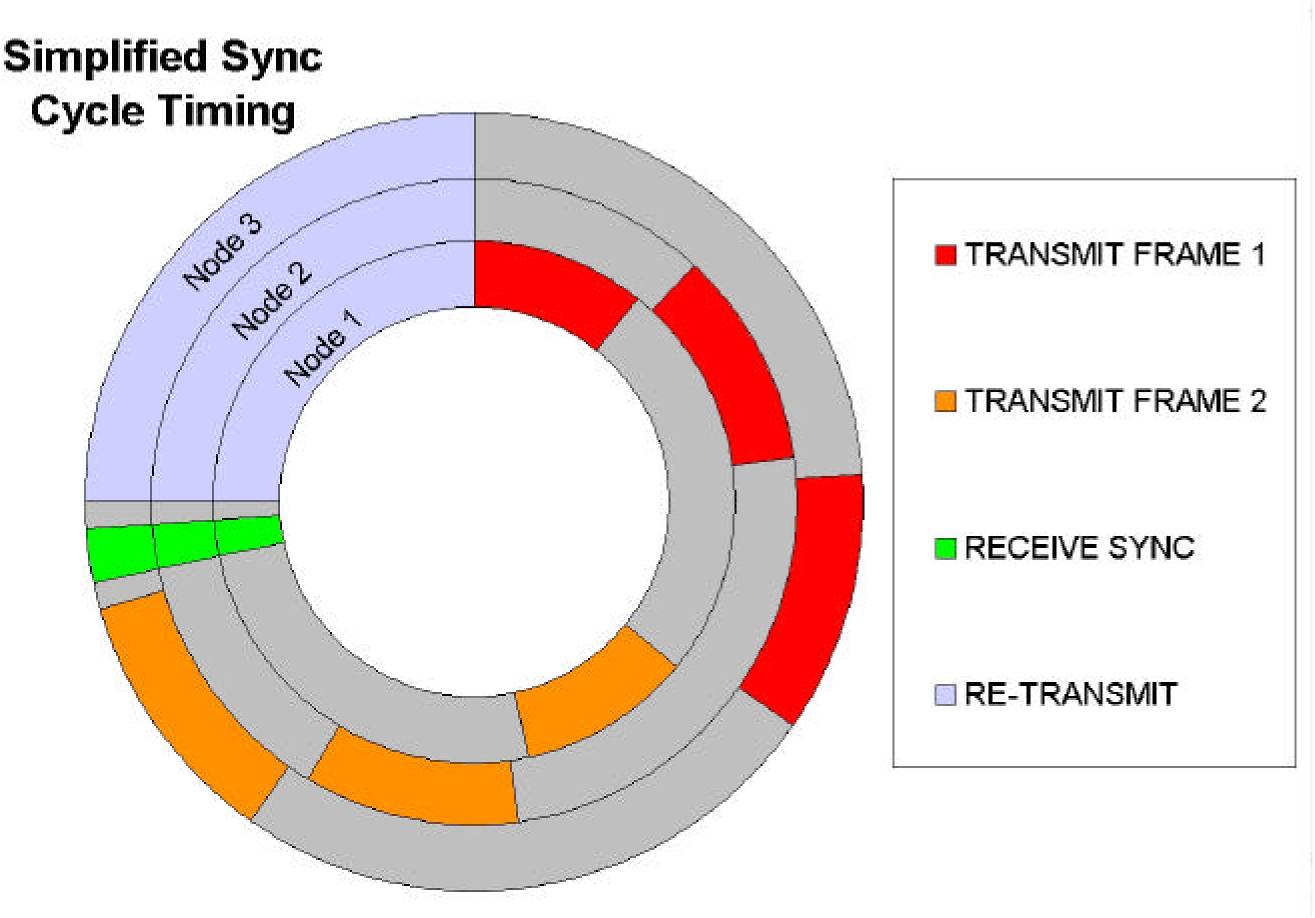

Figure 2, Simplified WAIS Synchronized Network Cycle Timing

Refer to Figure 2. The Simplified "Sync" Cycle Timing diagram is an example of a system setup with three RDGU's. The digitized data from each RDGU is divided into smaller packets for transmission. Small packets of data are used to decrease the effect of bit errors, since the system is setup such that a one-bit error in a packet requires retransmission of the entire packet. The packet size and number of packets are determined by the sample rates of the individual channels within the RDGU (node). The packets from the nodes are interleaved to increase RF channel efficiency. In the example above, Node 1 transmits the first of its two packets, and then Node 2 transmits the first of its two packets, and then Node 3 transmits the first of its two packets. The nodes then transmit their remaining packet in the same order. Since the number of data points sampled during each "sync" cycle is the identical every cycle, the timing of these transmissions remains constant for each setup. After all the data transmissions, there is a synchronization transmission from the CDCU. The timing of this transmission is used to synchronize the node's internal clocks. After the synchronization transmission, the remaining time in the "sync" cycle is used for retransmissions if necessary.

The WAIS synchronized network is unlike conventional wireless networks. For example, in a typical wireless LAN, a data transmission would send files to a printer or email to a server, all of which are not time critical (relatively). While this asynchronous nature is suitable for the applications intended, it does not satisfy typical aircraft data acquisition requiring synchronized data. The synchronized network approach satisfies aircraft data acquisition requirements by providing time determinant data to the destination with minimum fixed latency.

DECISIONS MADE DETERMINING THE FINAL WAIS CONFIGURATION

The power consumption for transducer excitation, especially for several 350 ohm strain gauges with 10 volt DC excitation in conjunction with the internal WAIS circuitry, would result in extremely low battery life for the small credit card size battery technologies being investigated to be internal to each WAIS unit. Consequently, application #2, internal battery operation was dismissed. If battery operation was required, it was decided to purchase aircraft qualified batteries to feed each WAIS unit. In turn, the WAIS internal power supply will regulate the battery voltage and then convert it to the proper levels for internal WAIS circuitry and transducer excitation. Because of this change, it was decided to make the system operate from 28 Vdc aircraft power resulting in the requirement for MIL-STD-704 compliant power supplies in all the WAIS units. This enabled each WAIS unit to operate either from 28 Vdc aircraft power and/or readily available 28 Vdc aircraft batteries depending on the application.

To guarantee WAIS compatibility with existing wired aircraft data acquisition systems; the CDCU analog output was deemed top priority, therefore the PCM output requirement was deferred. Consequently, the IRIG PCM output from application #3 was dismissed. If PCM output is a requirement for future applications, a PCM output can be developed. This could be easily added to the CDCU unit for all the WAIS units are modular employing the typical “sliced” architecture found in typical aircraft data acquisition systems.

CONCLUSION

The benefits of wireless data acquisition employing DSSS are real and significant. The synchronized wireless network technique described in this paper provides a practical solution to utilize network architecture to satisfy aircraft data acquisition requirements by delivering time determinant acquisition and delivery of data. As such, the WAIS architecture is capable of transmitting/reproducing instrumentation signals in real time. In doing this, the system can acquire signals which were previously impossible or impractical operating in a stand-alone configuration or be used as a vehicle to merge the data with other data into the host data acquisition system for subsequent telemetry and recording.

FUTURE THOUGHTS

History has shown that technology enables technology. Today’s wireless, transducer, and networking technologies will empower the next generation of terrestrial and aerospace hardware, which will in turn require even higher performance measurement systems to evaluate them. If the upward trends in wireless data capacity and subsequent decrease in available spectrum bandwidth are to continue, new technologies must merge with tried and true engineering wisdom. Wireless communication channels of the future must be highly spectrally efficient, transmitting more data while occupying less bandwidth. They must also learn to live with one another, backing off from unnecessary power levels to allow everyone to talk at the same time. Wideband Code Division Multiple Access (WCDMA) systems will use analog to digital converter technology to digitize large bandwidths at the Intermediate Frequency (IF) or Radio Frequency (RF) levels. Software will then digitally filter this data into channels and decode them as any modulation scheme the software supports. Any system will be able to talk to any other system, and all systems will have channel adaptation and equalization algorithms that will precode data to prevent multipath and correct for other channel degradations. Spectra will be used and simultaneously reused again. Commercial and Industrial products will move to higher and higher frequencies, with more expansive bandwidths to inhabit. Advances in materials technology and miniaturization will allow System On a Chip (SOC) systems to incorporate processors, storage and radio front ends on one die, making smart sensors that condition, process and transmit data the only option for high quality measurement and effortless installation. The road ahead is exciting indeed.

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