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Using GPS to enhance digital radio telemetry

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Abstract. The precise time available from the atomic clocks orbiting the earth in GPS satellites is used in many systems where time synchronization is important. The satellite clocks are monitored and adjusted by ground based control telemetry to within one microsecond of Universal Time. A number of commercial GPS receivers have the ability to provide a time synchronised output, typically one pulse per second, that is locked to this precise time base. This easily accessible timing source is often the justification for including a GPS receiver as an integral component of a complex system. There are additional benefits to be gained from integrating a GPS receiver as an embedded component of a mobile radio telemetry system, where GPS information can also be used to enhance the overall performance. This paper examines some research into combining some transmission techniques with time synchronisation from GPS receivers located in the mobile and in the base equipment to improve a digital radio channel. Using this combined approach, a reverse data channel can be eliminated where a single direction data stream is the predominant requirement.

Key words: 1PPS, FEC, SFH, TDMA, FDMA, Synchronisation.

1 Introduction

Radio communications systems for digital telemetry have undergone many enhancements over the past few decades. The ability to reliably transmit high speed digital data streams is a common requirement. As an example, the IEEE 802.11 Radio Frequency (RF) Local Area Network (LAN) has been widely used, not only in the office environment, but for many applications because of its relatively low cost. As with any RF data channel, some real challenges arise when the remote stations become mobile, and data rates are pushed higher. They suffer from well known propagation difficulties including multi-path and deep signal fade (Lee, 1993), all of which introduce data errors. While there are a number of methods used to correct these errors on the fly, the impact is often unacceptable transmission delays. Particularly damaging to throughput are the methods of successively reducing the data speed and transmission retries. For many static applications such as PC networks, error correction and data integrity are more important than variable delays. The delays experienced during error recovery must be tolerated by the user. For real time systems, this situation is unacceptable because it lengthens the transmission delay making the system response time unpredictable.

This project investigated the application of GPS within a digital telemetry system to bring advantages of robustness, simplification and to help solve some of these problems. This allowed the combining of some conventional methods in a system architecture that may not otherwise be considered viable.

2 802.11 RF LAN Tests

2.1 Initial equipment setup

The aim of this first step was to build and verify the equipment at each end of the radio link before introducing new radio channel equipment using GPS. Commercial 802.11b RF LAN equipment was used as the initial “proof of concept” transport medium connected as shown in Figure 1. 802.11 systems typically use Direct Sequence Spread Spectrum (DSSS) radio system in the licence-free Industrial Scientific and Medical (ISM) 2.4GHz band for the physical layer with a TCP/IP interface to the host equipment.

During development, an opportunity was taken to measure the real time performance of the RF LAN equipment under mobile conditions for later comparison. The accurate time information from a variable number of SuperStar II GPS receivers was transmitted back to a central computer. An embedded microprocessor in an FPGA was used to format a 150 byte message packet and to synchronise the transmission start time to the 1PPS signal from the GPS receiver. The message transmission was started from each remote station simultaneously at 100ms intervals. Because the transmission start time was known, this was able to be compared with the arrival time as measured at the central GPS receiver, in order to reveal the transmission delay.

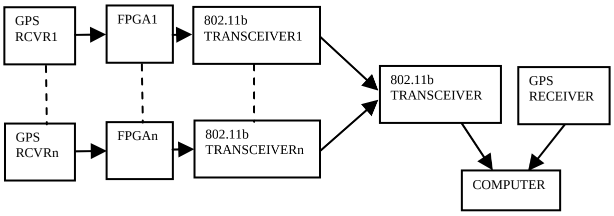

Figure 1. Test system data flow

2.2 Test results and analysis

Although the link was reliable under all Line Of Sight (LOS) conditions, the transmission delay was found to be quite unacceptable. The delay increased with the number of remote stations added, even under ideal conditions, as shown in Figure 2. The small drop in delay using 5 stations suggests that the data packet being sent was close to the optimum size for the internal RF protocol block. Delays of this type were expected because the conventional approach when un-correctable errors are detected in an RF LAN is to use an Automatic Repeat reQuest (ARQ) technique. Naturally, this reduces throughput as it takes extra time to re-send the data. Different message lengths and repetition rates were not tested but it is suspected that the data was broken into smaller blocks to help Forward Error Correction (FEC) and reduce the number of ARQ requests.

Changing the minimal tuning parameters for message length and wait time produced almost no improvement.

This was not intended to be an exhaustive test but it did show that the equipment is not ideal for real time deterministic transmission between more than 3 to 5 remote mobile stations sharing one base station.

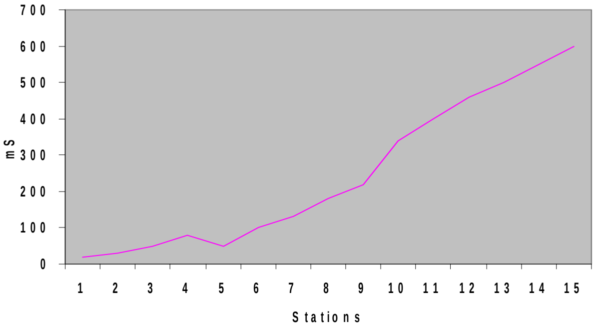

Figure 2. 802.11 average transmission delay

3 A GPS Synchronous solution

A new system was needed to deliver continuous bursts of real time digital data over a variable LOS distance of up to 5km from up to 30 remote mobile transmitters, at 100ms intervals. The remote transmitter needed to be light-weight, battery-operated and small enough to be man- portable. Consistent transmission delay for real time performance and data integrity were important.

The time base from the GPS network was employed as an integral part of the system. The One Pulse Per Second (1PPS), available from many GPS receivers (Mumford, 2003), was provided in this case by Novatel Superstar II receivers as a synchronous time base for both transmit and receive. Testing confirmed that the 1PPS signal between two Superstar II receivers was on average no more than 150ns apart.

This allowed the system to be fully synchronised at both ends using a combination of Slow Frequency Hopping (SFH), Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) to provide robust performance.

The ISM band transmitter output was set at a maximum of 400mW which allowed a run time of approximately 2 hours at full power using a small 950mAH cell phone size Lithium Ion battery. Receiver sensitivity was -100dB.

The data speed selected was 288Kbps giving a bit time of 3.47µs. This was fast enough to do the job but low enough to reduce excessive exposure to propagation-induced data errors.

The modulation scheme used was Gaussian Minimum Shift Keying (GMSK) for RF power amplifier efficiency and lower battery drain (Eberspacher and Vogel, 1999).

An FPGA was used in both the transmitter and receiver to perform signal processing, error recovery, frequency hop and synthesiser control functions.

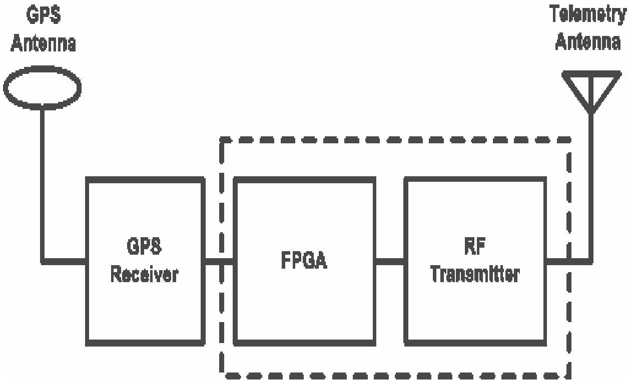

Figure 3. Remote transmitter architecture

3.1 Frequency Hopping Spread Spectrum (FHSS)

A lack of useable spectrum in the ISM band means that there is a risk of interference from other users. Slow Frequency Hopping (SFH) using 75 channels, spaced at 5MHz intervals between 2.405GHz and 2.470GHz, was chosen for this system. Although it is recognised that this approach is vulnerable to partial-band interference, to overcome this, the technique of Dual Frequency Diversity (DFD) (Proakis and Saheli, 2000) was used. The same information is transmitted on two successive frequency hops within the 100ms epoch and the received data from each hop is combined to improve interference rejection and anti-jam capability

Because 1PPS and GPS time were used to synchronise the system, the start time and duration of each hop is known at each transmitter-receiver pair. This simplified the design considerably because the usual adaptive timing recovery circuits and tracking procedures were not required.

3.2 Time Division Multiple Access (TDMA)

TDMA is a common technique used to increase capacity in a communication channel. A successful radio example of this is the Global System for Mobile communications (GSM) mobile telephone network. In order to maintain synchronisation of mobiles, the GSM base station transmits signals on a dedicated channel (Eberspacher and Vogel, 1999). The mobiles must use these signals to synchronise both time and operating frequency.

When using TDMA in a GPS synchronous system, the need for complicated time slot synchronising is eliminated. Each time slot is determined relative to the 1PPS signal. In this case the time slots chosen were 8.5ms long which allowed 5 different transmissions of 2448 bits at 288Kbps in each half (50ms) of the 100ms epoch, as shown in Figure 4.

3.3 Combining SFH, TDMA and FDMA

Using some custom-designed logic in an FPGA at each end of the radio link it was possible to combine both techniques described above with FDMA using the 1PPS signal.

With a pre-allocated orthogonal frequency hopping plan that was known to all transmitters and receivers, it was possible to dedicate a transmitter-receiver pair to a given channel in a given time slot. This effectively added FDMA to the system. Furthermore, it was possible to have a group of transmitter-receiver pairs operate in parallel, knowing that the frequency in use was exclusive to each member of the group. By distributing the channel occupancy of the receivers across the 100ms epoch, it was possible to use less receivers than remote transmitters. The receivers operated in every time slot while the transmitters only operated in two time slots per epoch to achieve DFD.

In this case there were 6 parallel operating receivers using 5 time slots per half epoch (50ms) receiving data from 30 remote transmitters.

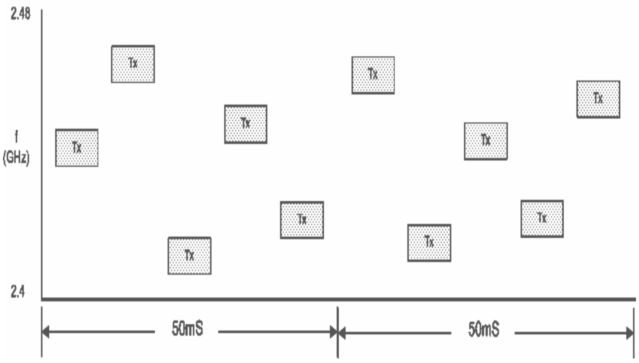

Figure 4. Time slots for one receiver

The maximised use of the spectrum and the radio equipment in this way requires that the hopping table entries are random to satisfy the channel occupancy time and avoid adjacent channel interference. The hopping table contained 300 entries which allowed sequential channel use over a 30 second period before repeating the sequence.

3.4 Error handling approaches

Error handling in transmission often employs a combination of procedures to detect and correct errors after receiving.

Because the data stream contained GPS measurements, there was an opportunity to interpolate some missing samples in downstream processing. Any samples that were completely unrecoverable due to failure to correct errors were marked as unusable. Based on this it was decided to eliminate the ARQ function from the architecture to reduce complexity and power consumption.

This is somewhat unique to the application, as it removes the need for a guaranteed delivery mechanism. In addition to using DFD, this did mean that stronger embedded data stream FEC measures were required to recover errors where they could have been recovered by ARQ.

A combination of approaches was used, as explained below.

3.4.1 Forward Error Correction (FEC)

The FEC technique used relies on the transmission of enough redundant data so that multiple bit errors can be corrected. In this case convolutional encoding was performed in the transmitter while the Viterbi algorithm (Viterbi and Omura 1979) was used for decoding in the receiver.

The encoder processed the message bits with k=1 and v=2 doubling the number of bits to give 100% data redundancy. The constraint length (K) was set to 9 to gain increased robustness. This was built into the transmitter FPGA using an additive shift register of K-1 stages to encode the data using polynomials (1) for the first bit and (2) for the second:

$$g_0(x) = 1+x+x^2+x^3+x^5+x^7+x^8 \qquad (1)$$

$$g_1(x) = 1+x+x^2+x^3+x^4+x^8 \qquad (2)$$

As the K value increases to strengthen the error correction capability, the downside is the increased processing load in the Viterbi decoder. Although the selection of K=9 was large, this posed no problem at the receiver end because an FPGA is ideally suited to this task.

3.4.2 Interleaving

Interleaving is used to reduce the susceptibility to fading by spreading the data so that all adjacent bits are separated. The level of protection against fade duration is impossible to set for all likely conditions of the radio channel because of the dynamically changing environment. Signal fading characteristics have been modelled (Lee, 1993) to show that fade rate increases as speed increases while fade depth is inversely proportional to speed, and can fluctuate over a large dynamic range from 10 dB to 50 dB.

In this case the message was broken into four blocks of 612 bits giving 612/288000 = 2.125ms of fade duration protection. The buffer was arranged as a rectangular matrix so that data was written by columns and extracted by rows, as shown in Figure 6. This is done inside a RAM buffer in the FPGA before transmit, and reconstructed using the reverse procedure in the receiver.

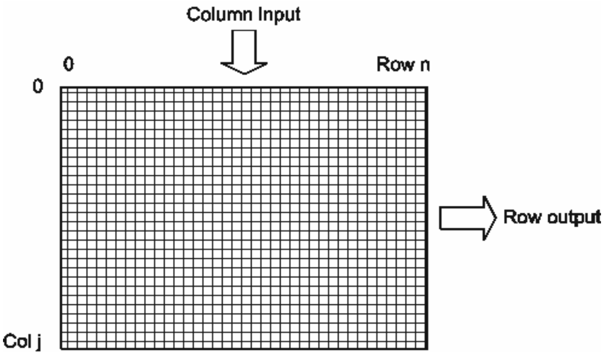

Figure 6. Transmit interleaver

3.4.3 Error checking

The ability to check for errors after receiving is essential because not all errors can be corrected. In this case two measures were used to confirm the reliability of the data.

The first was a 32 bit Cyclic Redundancy Check (CRC) generated from the buffer in the transmitter FPGA and appended to the message before transmission. This gave the ability to detect all error bursts of 32 bits or less at the receiver. Bursts greater than this were also detected but with only slightly less reliability.

The second integrity check was to verify that the 64 bit predicted GPS time value from the Superstar II receiver Measurement Record 23 was actually incrementing in 100ms steps. Any variation of this in the data from the telemetry receiver gave an indication of an error in the data.

4. Performance

The transmission delay was as expected from a synchronous system, and is shown overlayed with the RF LAN results in Figure 7. The transmission delay was 110ms, consistently measured regardless of the number of transmitters operating.

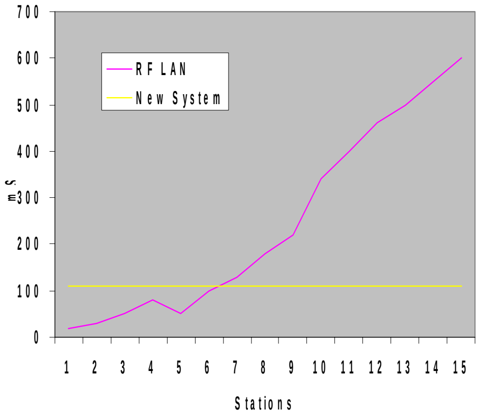

Figure 7. Transmission delay comparison

Table 1 gives a comparison of Bit Error Rates (BER) between different communication paths, including the new system described here.

Table 1. BER comparison

Communication path	Nominal BER
RF, No error correction	10-1 to 10-3
RF LAN	10-5
GSM	10-5 to 10-6
New telemetry system	10-7

5. Concluding remarks

GPS provides advantages when designed into a radio telemetry system because of the ability to make use of synchronisation. While this system has the benefit of multiple receivers, effectively providing a dedicated channel during each frequency hop, there is the added option to use TDMA. The concept allows design flexibility and scalability to meet a number of requirements limited only by the selected frequencies and the processing speed of the electronics.

One of the key system features is that when the number of remote transmitters is scaled up, there is no penalty in transmission delay. The limit may only be a regulatory issue with channel occupancy and dwell time.

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