Increasing Data Throughput in Radio Telemetry Systems

Introduction

In any data network attention must be given to the control protocol and signaling methods used in order to maximize its operational effectiveness. These issues are at least as important in radio based networks as in systems based on other transmission methods. As the use of radio-based solutions and applications increases, the pressures on the radio spectrum will become greater. High speed effective protocols and systems design will be essential features of radio data systems.

This application note will discuss factors affecting radio data network performance and present solutions based on integrated circuit technology to many of these issues. In general, it assumes the use of some form of packet data transmission rather than circuit switched data.

Increasing Data Speed

The most obvious method of increasing a network's efficiency is to maximize the data signaling speed. In nearly all types of radio-based data system, the transmission bandwidth of the data needs to be limited to fit into a licensable channel. Although some short-range systems do not suffer from extreme bandwidth limitations, this is not the case with wide-area data systems. If one assumes a working channel bandwidth of 12.5kHz at UHF, care is required to maximize the data that can be passed through this radio channel.

Two examples of appropriate methods are: Gaussian Filtered Minimum Shift Keying (GMSK) and Four Level Frequency Shift Keying (4L-FSK). As both can be implemented using traditional frequency modulation techniques, these methods are chosen as examples. While other signaling methods can provide faster transfer in a limited channel bandwidth, GMSK and 4L-FSK are effective and economic to implement in both the Baseband and RF sections of an equipment design. This is true as both modulation types can be dealt with using normal FM transmitter techniques and a traditional FM discriminator based receiver. This avoids the use of other more complex and expensive techniques such as I & Q or linear de/modulation.

i) Gaussian Filtered Minimum Shift Keying

In a GMSK system, the digital bit stream to be transmitted is passed through a Gaussian low pass filter. A Gaussian filter is a filter which when excited by an impulse outputs a Gaussian shaped output pulse. This is illustrated in Figure 1.

Impulse Input   "Gaussian" Lowpass Filter   Gaussian Shaped Output

Figure 1: Gaussian Filtered Minimum Shift Keying

When a digital bit stream is passed through such a filter, a marked reduction in transmission bandwidth occurs. In an optimum GMSK system, 8000b/s should pass through a 12.5kHz FM radio channel. For a further more detailed description of GMSK, readers are referred to Reference 1. The FM deviation should also be set to be equal to one-half of the data rate. For example, an 8000b/s GMSK data signal should be transmitted with a peak deviation of 4kHz or +/- 2kHz. Within the design of a GMSK system the maximum data rate, the bandwidth employed and the bit error rate can be traded against one another. The method described here provides an approximation to true GMSK. While not in-line with the textbook definition of GMSK, it still provides a simple and effective implementation of a GMSK system.

ii) Four Level Frequency Shift Keying

In a 4L-FSK system, the digital bit stream is split into a series of bit-pairs. Each bit-pair is then coded as one of four voltage levels and passed through a low pass filter section. It has been shown that the optimum channel shape for the passing of bandwidth limited digital data is that of a Raised Cosine. Filtering should be provided at the transmitter for the purpose of transmission bandwidth reduction and at the receiver for the limitation of noise bandwidth to the data detector. This filtering optimally should have an overall Raised Cosine response. The raised cosine is normally split equally in the transmitter and receiver as two Root-Raised Cosine low pass filters. As with GMSK the precise details of the bandwidth used, the maximum speed, and the bit error rate can be offset one against the other. A simplified representation of this process is shown in Figure 2.
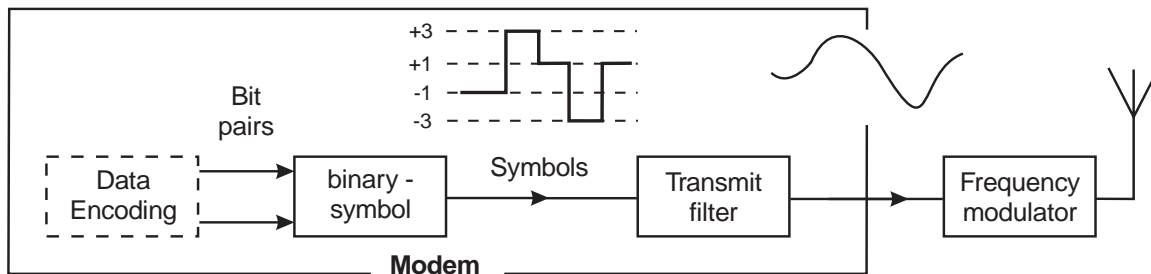

Figure 2:   Four Level Frequency Shift Keying

Using 4L-FSK 9600b/s can be achieved in 12.5kHz FM channels or 19200b/s in a 25kHz channel.

Either of the two modulation methods previously described can help to maximize data throughput by allowing fast data transfer at good bit error rates while using traditional FM techniques.

Data Coding to Reduce Retries and Collision Effects

A common source of problems in a radio data network is the data unfriendly environment offered by radio transmission. Systems that detect errors during transmission and simply ask for data to be resent can suffer from excessive numbers of retries and collisions. The more retries which occur, the more likely it is that further collisions and retries will occur. This situation will become progressively worse until the throughput of the system will reduce to nearly zero. In computer networks, a TCP/IP based LAN carried over Ethernet is an example system which works on the simple retry principle. In Ethernet every station can clearly 'hear' when any other station within the LAN is transmitting; this is not the case with radio based networks. Even so, a common benchmark for indicating that a network is reaching its maximum comfortable load is 40% packet time occupancy or put another way 0.4 Erlangs traffic loading. In radio the need to reduce to a minimum packet retries is therefore imperative. Without these methods, the traffic handling capacity of a radio-based system could reduce to well below this 40% figure.

The reduction in retries can be achieved using two distinct methods: The first procedure is to reduce the number of retries, which occur due to noise and interference. The second procedure is to use a suitable channel access method such that two active stations do not corrupt each others packets by transmitting simultaneously when their coverage areas overlap.

i) Forward Error Correction

In most packet data systems, error detection is performed by the use of Cyclic Redundancy Checking (CRC). However, to avoid retries the use of Forward Error Correction (FEC) is also required. In an FEC system, additional information is sent along with the data bytes to be transmitted. This additional information allows the receiving device to not only detect that errors have occurred but also to try and attempt to correct for some or all of these errors. As an example, a byte of 8-bits may be sent along with a further 4-bits of FEC information.

For example:

Bit position	0	1	2	3	4	5	6	7	8	9	10	11
Bit Description	b0	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11

Should an error occur in either information bits b0 to b7 or FEC bits f0 to f3, the FEC system will attempt to correct for these errors. In radio systems, most bit errors will occur due to a burst of noise or interference. This will have the effect of corrupting not just one or 2 bits per byte dotted along a frame but perhaps 20 bits all together while leaving the rest of the frame intact and without errors. An FEC system such as the one shown above will not be able to cope with such a situation since all the bits in a byte and the FEC information bits may all have been corrupted thus leaving no good information to work with. The use of a technique known as interleaving overcomes this problem.

Bit interleaving works by taking a number of data bytes and their associated FEC 'nibbles' and reading them into a table. As an example, if 10 bytes were used, this would be 80 information bits plus a further 40 FEC bits, making a total of 120 bits. This 120-bit, bit stream could be read into a table of 12 rows by 10 columns row by row.

```
000 001 002 003 004 005 006 007 008 009
010 011 012 013 014 015 016 017 018 019
020 021 022 023 024 025 026 027 028 029
030 031 032 033 034 035 036 037 038 039
040 041 042 043 044 045 046 047 048 049
050 051 052 053 054 055 056 057 058 059
060 061 ... ... ... ... ... ... ... ...
... ... ... ... ... ... ... ... 118 119
```

The bits are then read out of this table for transmission column by column thus in the above example the order of actual bit transmission is:

000 010 020 030 040 050 060 070 080 090 100 110 001 011 021 .... and so on.

This process is reversed in the receiving station to reconstruct the wanted data frame. The effect of this operation is that when a burst error occurs in the radio channel, it corrupts single bits spaced throughout the frame rather than blocks of bits in a single byte. Thus, the FEC process still has a good chance of being able to correct errors.

The MX-COM, Inc MX919 is an integrated circuit radio modem that includes FEC processing and bit-interleaving. The bit error rate (BER) curve in Figure 3 indicates that at S/N ratios of about 10dB a 3dB improvement in bit error rate can be achieved by additionally using FEC.
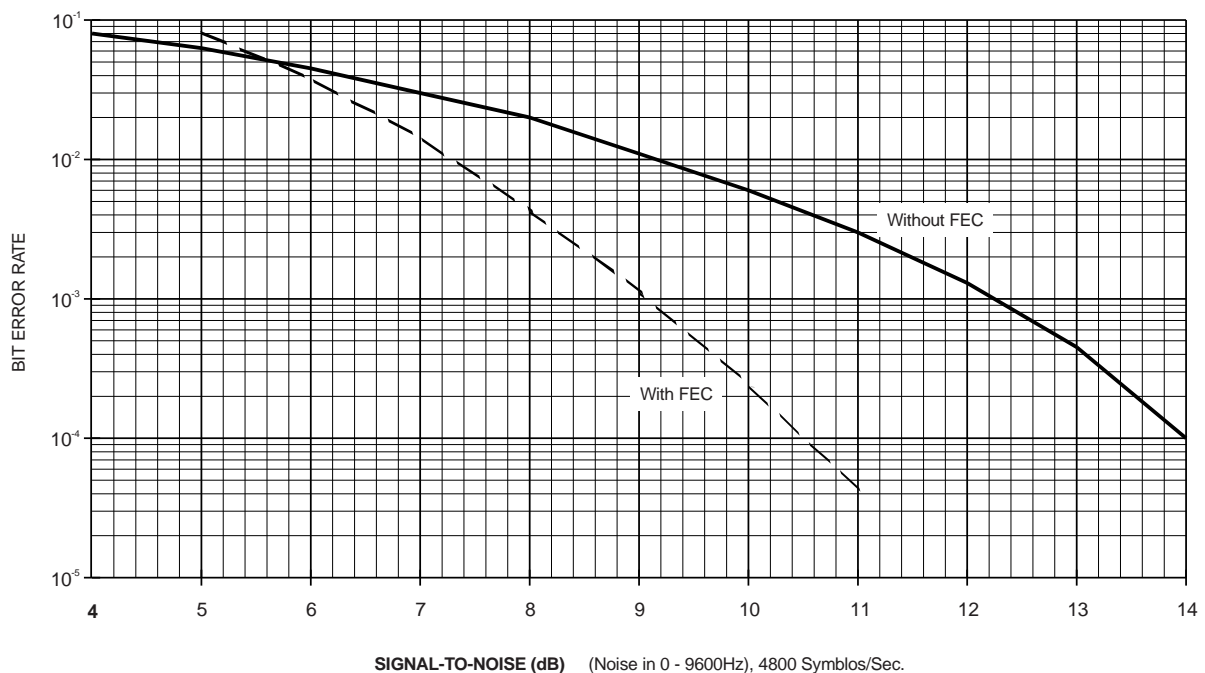

Figure 3:   Bit Error Rate

It will be noted that at a S/N ratio of 5.5dB, the FEC system breaks down and the BER is worse than not using FEC.

Once a system has FEC implemented, the number of retry attempts should be limited to a small number before the station concludes that transmission is not possible. This avoids stations generating lots of retries which have no hope of success and merely serve to increase the probability of collisions and band occupancy.

ii) The effect of FEC on the frequency reuse pattern

In addition to reducing, the number of retries which occur by providing an improvement in bit error rate; FEC also has an additional benefit. To achieve a certain bit error rate at the receiver, the transmitter power may be reduced by the S/N gain provided by the FEC. In the example of the MX919, this gain is around 3dB. The transmitter power could, therefore, be reduced by 3dB to achieve an equivalent coverage area. Since the interference distance of a transmitter increases by the square of its transmitter power, this gives coverage cells with much reduced interference overlap areas. Thought of another way this can be viewed as coverage areas with much more sharply defined cell boundaries. These sharp edges to cells allow a smaller reuse distance to be used to cover a specific area and thus increase the data traffic, which can be handled by a limited number of channels over a wide area. An illustration of this effect is shown in Figure 4.
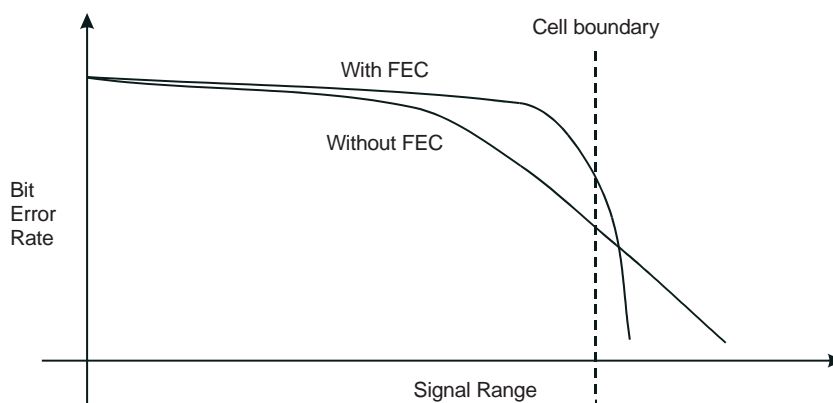

Figure 4:   Bit Error Rate Effect

The use of Slotted-Digital Sense Multiple Access to avoid data collisions

As previously described, in computer networks Ethernet is widely used to interconnect computers and to provide the data transport medium. Ethernet works by each station listening to the link and not transmitting data while another station is heard to be occupying the channel. When a station does transmit data, it also listens to its own signal and attempts to determine that its signal was not corrupted by another station during its transmission. It can do this because it assumes that if it decoded its own signals OK then so must all the other stations on its LAN. This is a valid assumption when the transmission medium is a coaxial cable! This channel access method is known as Carrier Sense Multiple Access/Collision Detection or CSMA/CD. The success of CSMA/CD in avoiding collisions is very dependent on a good Data Carrier Detect (DCD) system and on being able to detect collisions effectively. In radio systems, it can never be assumed that every station can hear every other station in fact the reverse is normally the case. No station can hear every other and what is heard and what is not is subject to many different effects from propagation, noise and interference. It has been shown by the designers of the ETSI specified 'HIPERLAN' system, a radio-based LAN, that in a radio-based system the DCD circuit has to be sensitive to 20dB below the point where data cannot be received successfully. In the case of most systems, this would need to be around the -15dB S/N point. Such a DCD is not a practical solution. In a half or full duplex radio system, collision detection while transmitting is not possible either because the Rx is not active during Tx or because if it is it suffers extreme de-sense problems. This analysis should demonstrate that a CSMA system or a CSMA/CD system cannot be used in a radio-based data network

Various approaches to channel access can be proposed to avoid the problems discussed above. These can involve a system in which a control station polls outstations for data thus ensuring only one station is active at anytime. This will avoid collisions but may also waste airtime polling stations that have no data to send or are not able to reply for some reason. A further alternative is the system known as DAMA or Demand Allocated Multiple Access in which stations indicate to a control station that they now wish to be considered active and

the control station allocates a time-slot to each active station. As the number of active stations increases, the data bandwidth allocated to each station in a set period reduces. This system is certainly much more effective than CSMA/CD and is widely used in satellite access systems where again no outstation can hear the other and there is a high risk of data collisions. However, some 'dead-time' will still occur and the efficiency will not be as high as a form of random-access or 'bandwidth-on-demand' system.

The particular method favored by the author is the so-called Slotted-Digital Sense Multiple Access S-DSMA algorithm. In S-DSMA, again a control station is used and this is assumed to be a duplex device. S-DSMA is a random access method similar to CSMA and thus avoids the 'dead-time' of polled or DAMA systems. It does also not introduce a significant amount of extra packet traffic to control its operation.

The operation is as follows:

> When the control station is transmitting data to an outstation, in addition to the information itself, it interleaves bits at regular intervals which indicate if the control stations receiver is busy or not. The control station is placed at a point in the system such that it can hear all the outstations in its cell and they only send data to it and receive data from it. The outstations are split frequency half duplex and do not transmit directly to each other. By monitoring the control stations 'receiver status bits', the outstation can determine if it is safe to transmit or not. If the control station states that its receiver is free the outstation is able to be sure that transmission can occur with a low risk of collision. In order to avoid two outstations both transmitting together when they both see the control station receiver is free, a random time delay is introduced at each outstation before transmission occurs. The delay allows one station to grab the channel before the other and the control station will then indicate that its receiver is no longer free. Thus, the second outstation must once again hold-off transmission.

By reducing the likelihood of collisions to a minimum and ensuring that only a good radio path is used for transferring data (to control station and back never from peer to peer) very high traffic loading of the channel can be achieved of the order of 75% or 0.75 Erlangs.

This effective system put together with the benefits of FEC and sharply defined cell boundaries can prove extremely effective. The Motorola mobile data system known as DataTAC^{TM}, which employs these techniques, can support around 1500 outstations per control station.

This is highlighted in Reference 2.

Simple implementation of these complex solutions

Consumer Microcircuits Limited have launched a range of integrated circuits which remove from the design of radio data networks many of the problems discussed in this paper. Known as the MX9x9 series of devices each product comes in a 24-pin Shrunk Small Outline Package and operates from a minimum supply voltage of 3.0 volts. The current consumption is of the order of 2.5mA at 3.3 volts.

Each device provides a microprocessor interface and analogue input/outputs suitable for connection to a typical FM transceiver implementation. In addition, each circuit includes packet framing, bit sync and frame sync recovery, Forward Error Correction calculation and checking, a bit de-/interleaver and Cyclic Redundancy Check calculation and checking. A data quality register is provided to enable each host microprocessor to assess the signal quality of an incoming data signal.

The devices in the MX-COM MX9x9 series have the following device specific features.

The MX909A provides a GMSK based data signaling modem in addition to the features discussed above it also includes a data randomizer to improve the performance of the GMSK system.

The MX919B provides a 4L-FSK based modem in addition to the common features of the MX9x9 range of ICs.

The MX929B provides a 4L-FSK modem and automatic handling of interleaved S-DSMA status bits in addition to the common features outlined previously.

These integrated circuits make the design of fast effective radio data networks much more easily achieved.

Conclusion

This paper has shown how the use of effective data modulation methods, forward error correction and the S-DSMA channel access technique can maximize the effectiveness of a radio data system. This allows optimum spectrum use and provides a good quality service for the users of such a system. The importance of these features can only increase as the use of radio based data systems also increases. The paper has also indicated that off-the-shelf solutions exist in the form of integrated circuits to help a system designer make full use of the methods discussed.

References:

1:    MX589 GMSK Modem Application Note

(MX-COM, Inc Publication Doc. # 20830074.002)

2:    The RD-LAP Air Interface Protocol

(Ronald Gerhards and Pierre Dupont, INTERCOMM 93)