

DCS bandwidth requirements for CBTC and CCTV

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Abstract

The Alcatel ComTrac DCS system uses open standards protocols. Of these standards, contention-based communications systems with guaranteed access and superior error management, are best suited to both the CBTC and the CCTV applications. ComTrac is based on the Ethernet family of network standards, with IEEE 802.3 for the wired portion and IEEE 802.11 standard for the wireless portion. Within this wireless standard, frequency hopping spread spectrum (FHSS) is preferred over direct sequence spread spectrum (DSSS) because of the superior interference immunity and the ability to co-locate several access points. In the network design, priority is given to the CBTC communications requirements. Based on a typical system, an 802.11 transmission rate of 1 MHz can support more than 10 trains simultaneously through any access point. The minimum bandwidth requirement is 25 such channels of 1 MHz each (in a frequency hopping configuration) for a total of 25 MHz. This will ensure less than a 0.1% probability that a train will be halted due to a loss of communications in any 3-month period of continuous operation. The 25 individual frequencies can be selected from at least one of the 802.11 standard pseudo-random hop sets. Furthermore, additional non-interfering hop-sets can be selected for simultaneous use by a CCTV system that can accommodate full-motion video at 8 frames per second.

1 Introduction

Applicants to regulatory authorities, for the allocation of dedicated bandwidth for their data communications system, have a feasible alternative to using the full 80 MHz bandwidth required by 802.11 FHSS users of the license-exempt bands. There is technical justification for no more than 25 MHz of bandwidth for the



proper operation of a Communications Based Train Control (CBTC) system that concurrently supports a Closed Circuit Television (CCTV) from the train to the wayside.

To exemplify, this paper examines the bandwidth requirements of Alcatel's ComTrac Data Communications System (DCS) that are determined by the IEEE 802.11 FHSS (frequency hopping spread spectrum) standard [1]. The FHSS option is preferred over the direct sequence (DSSS) option because of the ability to co-locate of access points and because of superior interference mitigation. This standard allows for (and regulatory authorities often require) up to approximately 80 MHz of total operating bandwidth, although only 1 MHz is occupied at any one time. The system can technically operate in less total bandwidth by restricting the frequency hopping range. The minimum bandwidth required by the DCS to properly support both CBTC and CCTV depends on system performance requirements and the anticipated co-user and interference environment.

2 DCS Requirements for CBTC

A typical CBTC system uses packet-based transmission of train control information. Such a scheme is well suited to the short duty cycle nature of contention-based communications systems and is compatible with IP based networks. Data packets are exchanged between control equipment and trains on a poll-response basis with a typical cycle time of about 70 ms. To accommodate this requirement, the preferred DCS design uses multiple-access packet transmission techniques, based on an open-standards radio network scheme (i.e. 802.11 radio Ethernet [1]) to share the available bandwidth. A contention-based scheme is preferred because:

It is stochastic and not deterministic. This means there is never a chance of not having a circuit available when it is required. This is critical for the continued operation with a CBTC system.

It does not require forward error correction. Instead it relies on error detection and retransmission. This means that a received packet can be relied on to be error free rather than having to deal with the possibility of residual errors.

It is much more immune to narrow band, short duration interference. A transmission that is interfered with is treated the same way as a collision.

The contention-based access scheme specified by the 802.11 standard is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). We can calculate the throughput capacity of a radio channel in the following way. All users are assumed to have the same size packets and use the same transmission rate r_b . If they all begin transmission at the start of predefined uniform intervals (slotted Aloha time slots) but are otherwise randomly occurring (Poisson arrivals), the throughput bit rate, r_t , can be expressed as,

$$r_t / r_b = (r_s / r_b) e^{-(r_s / r_b)} \quad (1)$$

where r_s is the offered load (including retries). This expression has a maximum value of $r_t = 0.368 r_b$ and occurs when $r_s = r_b$. At this load, about two thirds of all



transmissions are retries. Note that the situation is actually more complicated than this because collision avoidance is used rather than collision detection (a mobile station is advised by an access point if there is a collision rather than detecting it directly). Nevertheless, the basic capacity properties of the channel remain the same. The maximum throughput for a 1 Mb/s transmission rate is therefore 368 kb/s. In practice, however, it is preferred to operate well below this maximum in order to minimize the number of retries, especially if interference is present.

A typical CBTC system has an average two-way data transmission requirement of around 8 kb/s from any one train. For a system designed to handle up to 10 trains simultaneously over any particular radio link, the total throughput required for a given link is 80 kb/s. The overhead required by the packet transmission scheme increases this by a factor of 2.5 (the packet payloads are relatively small), therefore the net data throughput of one radio link is 200 kb/s. According to (1) this represents the maximum throughput for a system that has a 543 kb/s transmission bit rate. The 802.11 standard rate of 1 Mb/s would meet this requirement with a margin factor of almost 2.

3 DCS Requirements for CCTV

The DCS design is also required to transmit CCTV data packets from a mobile train to the wayside where they can be relayed to central monitoring equipment. For this application the access requirement can be reduced to that of a single user over any particular radio channel. A CSMA/CA scheme with a single access can support a data throughput that exceeds 70% of the packet transmission rate (e.g. as measured using a typical radio). Thus a 1 Mb/s rate can support a throughput of more than 700 kb/s. A high quality full-motion CCTV signal can be transmitted, at a refresh rate of up to 8 frames per second, with this throughput. Thus a single 802.11 FHSS radio channel can support CCTV transmission. As an option, the same radio channel can also support 4 simultaneous CCTV signals by reducing the screen area of each picture (i.e. by having the 4 pictures on the display screen together).

The characteristics of a single access scheme, with respect to occupied bandwidth and immunity from noise, are otherwise the same as for a multiple access scheme. The video signal packets are buffered to accommodate variations in transmission latency.

4 Basic modulation scheme

Consider for the moment an 802.11 system without frequency hopping. The modulation method is 2-level Gaussian Frequency Shift Keying (2-GFSK) with a filter BT of 0.5, a modulation index of 0.32, and non-coherent detection. The transmission bit rate for each burst is 1 Mb/s and the occupied bandwidth is 1 MHz. There is an option to operate at 2 Mb/s using 4-level GMSK, however this does not occupy any more bandwidth because the symbol rate is still 1 Mb/s.



At 1 Mb/s the bit period is 1 μ s. In this time period a radio signal propagates 300 m. The additional distances introduced by grazing angle reflection from tunnel walls and the ground are much shorter than this and therefore there will not be any significant delay spread problems. Also, at a centre frequency in the 2.4 GHz (ISM) band, a train traveling at 100 km/hr moves much less than a millimeter during a bit period. This is only a fraction of the 0.125 m wavelength, therefore, there is no significant Doppler shift. Note, however, that there can be significant surface reflection problems causing deep nulls in the received signal strength at certain distances from the transmitter. The precise location and depth of these nulls depends on the exact locations of the transmitting and receiving antennas relative to these reflecting surfaces. For this reason two mobile antennas are used on a train to provide diversity of signal paths.

Technically a CSMA/CA system can operate within a single 1 MHz band without frequency hopping. The MAC and the physical layer functions are the same. The only difference is that the frequency is not changed from one transmission to the next. Multiple users can still access the channel on a contention basis in order to share the link. The throughput remains the same, but the centre frequency can be any value subject to availability and propagation considerations. However, this mode of operation does not provide any protection against interference and does not allow co-location of radio access points since only one radio is permitted to manage the accesses (using the carrier avoidance scheme).

The 2-GFSK modulation scheme specified used by 802.11 has a bandwidth efficiency of 1.0 (1 Mb/s symbol rate in 1 MHz of occupied bandwidth). Other modulation schemes, such as MSK or PSK and its variants, could be considered, as well as coherent demodulation methods. Indeed, higher-level modulation methods may achieve a better efficiency. However, considering the additional costs incurred, and in the light of all the benefits that accrue from frequency hopping and the use of an open standard, there is no real benefit to be gained.

5 Requirements for access point co-location

For CBTC, a reliable DCS design requires that the radio access points (APs) along the guideway be arranged to have overlapping areas of coverage. This is to guarantee continuous coverage to a passing train with redundancy (e.g. even if one of the APs fails). In order to achieve this it is necessary that a number of different APs be “visible” to a train mobile radio (MR) at any one time. This is a form of co-location where more than one AP covers a given physical area. The MR will decide which AP it wishes to communicate with as part of the physical medium access protocol of 802.11, however, each AP must operate on a separate channel so as not to interfere with each other.

In other situations, such as at a maintenance yard, the number of trains requiring access from the same physical area may exceed the design limit of 10. In these cases it is necessary to provide additional APs to cover the same area. This is another reason for co-location and for more that one channel on which to operate the system.



Typically, a DCS requires a minimum of 5 separate channels to accommodate these co-locations. The total occupied bandwidth of these 5 channels would be 5 MHz (without any guard bands).

The requirements for co-location with the CCTV system are not as stringent. Overlapping coverage is not a requirement for redundancy purposes but it is still needed for continuous coverage. Without overlaps only 3 co-located APs need to be accommodated. This means that, in practice, a minimum of 3 MHz of bandwidth is required for the CCTV.

6 Minimum bandwidth requirement – ideal vs practical

The ideal total minimum bandwidth for CBTC and CCTV services, using a non-frequency hopping scheme, is the sum of the CBTC and CCTV requirements, or 8 MHz. Although this scheme is a departure from the 802.11 FHSS standard, the essential multiple access features have been retained. All the advantages of the standard MAC layer functionality and physical layer transmission properties are available. However, because of our assumption of no frequency hopping, there is no protection against interference, either unintentional or deliberate. This applies to noise and co-users of the band if it is shared, or to noise and accidental or deliberate interference if it is a dedicated band.

In particular there is no means to avoid an interfering signal. The only mechanism available to mitigate the effects is to retransmit a packet. This would quickly consume the available channel capacity if the interference were persistent. In fact the scheme is extremely vulnerable to a denial-of-service attack by even a low level narrow-band interfering signal. Note that a dedicated (regulated) band would provide no further protection to such a deliberate attack. Indeed any narrow-band radio access scheme will be similarly vulnerable. An interfering signal (deliberate or not) could bring a train to a stop and, depending on the location, could tie up a large portion of the transit system.

It is essential that a CBTC system provide a highly reliable and safe communications service. From a safety perspective the DCS should be compliant with CENELAC EN 50159-2 for open communications systems. The safe strategy on losing communications or receiving messages in error is to stop the train. From an operational point of view, however, there must be a minimum disruption to service. Therefore, it is important that messages that fail to get through because of collisions or interference be retransmitted until they do get through. Despite the ruggedness of the retransmission protocol associated with 802.11, there is always a small probability that communications will be lost. This can happen if, by chance, the messages are repeatedly interfered with.

A reliable DCS design must have several layers of redundancy. For example, on the train there is independent DCS equipment at each end. For a train to come to a stop communications must be lost at both ends simultaneously. Communications is considered lost if there is a period (for example 3 seconds) during which no valid message is received. If the maximum polling period to any one train is 1 second, as in the ComTrac system, then there must be four successive corrupt messages before communications is lost. A typical



performance specification for a CBTC requires that the probability of any train in the system stopping due to lost communications, P_s , is less than a certain value over a certain time period. For example P_s must be less than .1% for all the trains in the system over a 3-month period. We assume an equipment availability of 100% for this calculation. For the Alcatel CBTC system, in these circumstances, this amounts to some 100 million messages being exchanged between all the trains and the wayside equipment. We can find the corresponding probability that a particular message can be missed as follows.

The probability of any single message causing a train-stopping event is,

$$P_m = (1/100 \text{ million}) \times .001 = 10^{-11}.$$

Since communications must be lost to both ends simultaneously, the probability of any message to either end causing a train-stopping event is,

$$P_{me} = (P_m)^{1/2} = 3.16 \times 10^{-6}.$$

Since this must happen 4 times in succession, the probability that each of the 4 successive messages is lost is,

$$P_{ms} = (P_{me})^{1/4} = 0.042.$$

If we now assume that the messages are lost due to the random occurrence of interference, then the probability that this interference occurs within the 1 MHz occupied by the transmission must be less than 0.042 for each message transmission. This interference is further assumed to completely disrupt the message regardless of where it occurs within the 1 MHz band (or indeed over the entire band). Error correction is of no help in this situation.

However, the above model is not very realistic. If interference occurs during one message transmission there is a high probability that it will still be there for the next 3 messages, especially if it is deliberate. The system will not be able to meet the service requirement unless the probability of occurrence of the interference is close to the P_{me} value of 3.16×10^{-6} , which is unlikely. The most effective way to deal with the interference is to avoid it, and the most effective way to avoid it is to move to a different frequency for the next (or retransmitted) message. The question is how much to move. It is difficult to quantify the extent of the interference but if it is deliberate it is not likely to be more than 10 MHz wide. This would mean that each channel of the system would need two frequencies about 10 MHz apart. The difficulty with this approach is that some means must be provided so that a receiver knows what frequency is to be used next. The 802.11 FHSS scheme solves this problem by having a number of different frequencies, or channels, available. This is known as a hop set. The radios use these frequencies in a pseudo-random, but known, sequence. The problem then reduces to finding the probability that the interference occupies the same 1 MHz frequency band at the same time as the radio transmission. If there are N contiguous but non-overlapping channels available then the probability



that the interference is in a given channel is $1/N$. By equating this to the required probability $P_{ms} = 0.042$ we can determine that the minimum number of channels required is $N = 1/0.042 = 23.7$, corresponding to a bandwidth of 23.7 MHz.

One part of the 802.11 standard calls for a 25-channel hop sequence, occupying 25 MHz of bandwidth (i.e. the standard for Japan). Therefore it is convenient to specify 25 MHz as the minimum required operating bandwidth for a CBTC system. The hop sequences defined for 25 channels can be adapted for any other centre frequency and will satisfy the minimum bandwidth requirement of 23.7 MHz.

Another feature of the frequency-hopping scheme is that orthogonal hop sequences can be defined which never use the same frequency at the same time. This is a convenient way of providing multiple accesses for several users without any co-user interference. Therefore the CCTV service can be provided simultaneously over the same 25 MHz bandwidth as the CBTC service.

7 Conclusion

Alcatel's DCS design philosophy is to deal with adverse conditions as and when they arise, rather than to try to minimize their occurrence. In other words to use packet retransmission rather than forward error correcting, to use contention-based access rather than deterministic access, to use frequency hopping spread spectrum rather than to try to guarantee interference-free spectrum.

The DCS is required to meet stringent service availability requirements (in addition to a high equipment availability). The requirements for both CBTC and CCTV have been analyzed, along with the performance needed from a DCS that meets these requirements. As a result it has been demonstrated that although the system can technically operate in as little as 8 MHz of bandwidth (for both CBTC and CCTV) the minimum practical bandwidth, required to give the level of service needed in an interference environment, is 25 MHz.

A 25 MHz minimum bandwidth achieves the following:

- a) Meets the stringent availability requirements of a CBTC system
- b) Accommodates 8 kb/s full-duplex data links simultaneously with up to 10 trains over any one radio link,
- c) Simultaneously accommodates a CCTV system with up to 4 full motion pictures at 8 frames per second each,
- d) Maintains the full advantage of contention-based (Ethernet) access,
- e) Maintains the full advantage of an open standard-based (802.11 FHSS) radio system,
- f) Provides maximum protection for both intentional and unintentional interference.

References

- [1] IEEE Std 802.11 Wireless LAN Medium Access Control and Physical Layer Specifications.

