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Wireless Access Methods and Physical Layer Specifications

CALCULATING DECODED BIT-ERROR RATES OF 802.11 PHYSICAL LAYER EQUIPMENT USING ERROR RATE MEASUREMENTS OF ENTIRE TRANSMISSIONS

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ABSTRACT

This submission deals at some length with the issue of determining the Bit-Error Rate of received data for the purpose of 802.11 "Wireless Compliance Testing", by measuring only the Error Rate of an ensemble of complete radio transmissions and calculating the actual BER from this data. First, the background, showing the need for this exercise, is given. Then the necessary transmission length and BER parameter characteristics are explained. Next, the necessary simple statistical formulas are derived, and applied to the BER of 10^{-5}. After that, these formulas are applied to a larger BER, asserted to be important to the Standard. Finally, there is a short discussion on Frame Acquisition as it relates to the main issue.

In a surprise additional section, it is suggested that through the use of "Design For Test" practices, BER can indeed be measured directly over the air.

BACKGROUND

In order to facilitate practical Conformance Testing, on 9 and 10 May 1995, the FH PHY group voted to substitute the error rate of complete transmissions (which is shown in the record as 'Frame-Error Rate, or FER') for Bit-Error Rate in all of its Conformance Specifications. Owing to a lack of understanding of BER/FER dynamics, the master vote resulted in only a simple majority, not a 3/4 majority. Although FER is the basic indicator of WLAN receiver performance, the participants recognize that BER is the fundamental indicator of demodulator performance and system sensitivity, and it was not universally understood how a particular FER number represents a particular BER number. The purpose of this submission is to explain more precisely how this conversion can actually be performed within the present context.

Considerations of measuring only FER and using those results to calculate BER were an outgrowth of the FH PHY group's initial informal discussions on conformance testing which took place at the January San Jose session. Specifically, we started with the idea that the antenna is an integral part of the PHY and that valid system tests cannot be conducted with it removed [1,2]. "Once the decision has been made that radiative rather than conducted measurements are appropriate, avoiding contamination of the region of space around the Unit under Test assumes great importance. The unit (assumed here to be a PCMCIA card) needs to be tested in its actual operating environment, which makes it very difficult to add test wires for special access to circuit nodes. These considerations led to our discussions of changing Bit-Error Rate specifications to Block-Error Rate." [2]

The main questions being asked are: "How can one determine Bit-Error Rate (BER) by measuring Frame-Error Rate (FER)? If not, why purport to substitute FER for BER?" The simple question was "If you are only counting good and bad frames, how does one know how many errors were in the bad frames? Without this knowledge, how can one calculate the BER?"

CALCULATING BER FROM FER

The simple answer is that for the small BERs which are relevant here, the probability of more than one error within a short frame is negligible. Unlike the plotting of a normal BER curve, which displays E_b/N_0 for all BERs from, say 10^{-2} to 10^{-7} (used in the development of the Radio PHY), the measurements made here for conformance testing need only center around 10^{-5}. At this BER:

1. Except once in a very great while, there should be at most one error in any given frame, if the frame length is sufficiently short.
2. The probability of losing a frame with no bit errors (i.e. because acquisition was not achieved) is negligible.

First, we shall deal with the statistics relating BER in the main body of the frame to FER. Later, we shall see how the acquisition process itself contributes to the BER.

Before performing this elementary calculation, it is important to specify that even though actual field conditions will often result in noise, fading, and interference which cause "bursty" error statistics, 802.11 conformance testing will demand that nodes deal merely with stationary Gaussian noise, in which the probability of error distribution is uniform throughout the frame. It is also important to specify for the purposes of this calculation that each bit is decoded independently. For instance, if differential decoding is used, when the BER is calculated from the FER using the formula derived here, the result should be doubled.

The major questions which must be answered by the calculations are:

1. For a given BER and frame length, what percentage of all imperfect frames have <u>exactly</u> one error?

2. Can the frame length be optimized to increase this percentage such that the number of extra errors (i.e. over and above one per frame) is small enough to be neglected, and, at 1 Mb/sec, it will not take too long to gather enough data (total number of errors) to obtain a statistically meaningful error rate measurement?
3. If Criterion #2 above cannot be met, can the calculated distribution of the number of errors for all imperfect frames be used to derive BER from FER? (In other words, does the assumption of Gaussian statistics and known frame length, plus a large percentage of error free frames, allow one to accurately calculate BER from FER?)

It may even be possible, even necessary, to uncover problems with the detection process which cause sub-optimal results. The Draft Standard specifies a certain maximum BER (or corresponding FER) at a given RF Input level. It does not specify what error rates must exist at higher signal levels, *yet it is possible for an inadequately designed PHY to show no error rate improvement at higher RF Input levels and/or an extraordinary degradation at lower Input levels. It is therefore important to add a provision to the Standard which specifies some (reasonably small) portion of a BER or FER curve instead of just a single point.*

The Calculations

For now, however, let us begin the primary task by deriving a formula which converts raw BER and a given frame length to FER:

1. If the Bit-Error Rate is B, by definition, the probability that any single bit is decoded incorrectly (irrespective of any other bit) is B; so the probability that any such single bit is decoded correctly is 1-B.
2. Using the previously stated assumption that each bit is independently decoded and has an equal probability of being decoded correctly (a statistically stationary sample), the probability of correctly decoding all (N) bits in the frame is $(1\text{-}B)^N$. (This statement is true for any arbitrary set of N bits, successive or otherwise.)
3. Therefore, the probability of not decoding all the bits in the frame correctly (making one or more errors)--the Frame Error Rate--is $1-(1-B)^N$.

Let us use this formula in a practical situation. First, it is stated without proof that any BER experiment (direct or derived) which produces at least 1000 errors allows a sufficiently small confidence band for the present purpose. (If this statement does not receive FH PHY participants' consensus, the Author will derive the confidence band and show that in an addendum to this submission.)

At a BER of 10^{-5}, 10^8 bits need to be sent to obtain (on the average) 1000 errors. At 1 Mb/sec, this would take 100 seconds plus the overheads of sending multiple transmissions. If each transmission has 400 bytes (3200 bits) under control of the CRC, 31,250 transmissions will be needed to send 10^8 bits. The overhead for each transmission will take about 100 µsec; so, including additional time between transmissions, less than two minutes will be required for the test.

Using the above formula to calculate the probability of receiving one or more bits incorrectly within a 3200 bit frame (BER of 10^{-5}), the FER is 0.0314936. Therefore, with 31,250 transmissions sent, on the average, 984.174 of them will contain one or more of the 1000 errors. The presumption (related to the small percentage difference between 984 and 1000) is that the probability of having more than two errors in a single frame is negligibly small; if so, 16 of these 984 frames have two errors.

In order to check this presumption, it is necessary to derive one more simple formula--the probability of obtaining <u>exactly</u> one error in a frame (of a given size, N, and given BER, B).

1. By definition, the probability that any single bit is decoded incorrectly (irrespective of any other bit) is B; so the probability that any such single bit is decoded correctly is 1-B.
2. For any group of independently decoded bits, the probability of obtaining the sequence in which any one bit is decoded incorrectly and all others are decoded correctly:
   C, C, C,...C, I, C, C,...C is (1-B)(1-B)(1-B)...(1-B)B(1-B)(1-B)...(1-B), or, $B(1-B)^{(N-1)}$.
3. To this must be added the (equal) probabilities of each other single bit decoded incorrectly, such as C, C, C,...C, C, I, C,...C; as each configuration is an alternative way to obtain exactly one bit error in the frame. As the incorrectly decoded bit can be any one of the N, the total probability is $NB(1-B)^{(N-1)}$.

Applying this formula to the present example of $B=10^{-5}$ and N=3200, we obtain the probability 0.0309925 of seeing exactly one bit error. As expected, the probability of seeing only one bit error in the frame is less than that of seeing one or more errors. Applying this result to the same 31,250 frames shows that on the average 968.516 frames will have one bit error; so:
984.174-968.516=15.658 of the frames have the remaining 1000-968.516=31.484 bit errors.
31.484/15.658=2.0107 bit errors per frame. Thus, to a high degree of approximation, all the bit errors in the average group of 3200-bit 31,250 frames have been accounted for:

- 30,265.826 frames contain no bit errors and are therefore received with a good CRC.
- 968.516 frames contain one bit error.
- 15.658 frames each contain two bit errors.

It has therefore been shown that a BER of 10^{-5} can be determined accurately by measuring FER under the above conditions. For this size packet, an FER of 0.0315 or better indicates that a BER of 10^{-5} is being met or bettered. It is claimed that these calculations, plus the assumptions of Gaussian noise, independent decoding of each bit, and stationarity, indicate that all three of the above "major questions" have been satisfactorily answered.

Other BERs

As mentioned above, the Committee should consider adding to the Draft Standard a small number of additional points on the sensitivity curve in order to reduce the chances of hidden defects. Let us therefore use the above formulas to show that a BER of 10^{-4} can be computed from FER measurements.

In this case, only 10^7 bits need be sent to obtain 1000 bit errors. Let us send 31,250 transmissions each containing only 320 bits (40 bytes). The probability of obtaining only one bit error is

0.030995, and that of obtaining one or more is 0.031495. These results translate to 968.505 frames each with one bit error and 15.713 frames each with two errors. The test time is about 15 seconds.

The Frame Acquisition Issue

Now that it has been shown that for short enough frame sizes, FER can represent BER, it is necessary to make sure the Frame Acquisition (determination of the bit boundaries) process will not ruin the BER measurement by contributing to Frame failures (which would be indistinguishable from true bit errors and cause the derived BER to appear higher than actual). *Note: The previous sentence is not always true. The Test transmitting node could count the frames being sent, and if the receive node under test is configured to deliver a "packet acquired" signal to the host test system, it could distinguish between a bad CRC and no acquisition. The test results would have three columns: "good CRC", "bad CRC", and "no CRC"; or "number of frames sent", "good CRCs received", and "bad CRCs received"; where only the last two columns would be used to calculate BER; as the excess of first column over the total of the last two represents acquisition failures, which need not be counted for BER statistics.*

Even if the node and test system cannot be configured in that manner, there should be no problem confusing bit errors with failure to acquire. As the input signal level is increased from well below threshold, a few dB before the Bit-Error Rate is usable (say 10^{-2} to 10^{-3}), a properly operating acquisition system will already be acquiring virtually all of the frames. Owing to its repetitious nature, the effective signal bandwidth is much more narrow for the preamble ('idle pattern') than for random data, and a properly designed acquisition system takes advantage of this fact in order to achieve robustness. Thus, the FER measurement should not be affected at all by the frame acquisition process.

Prior to checking BER via the above FER procedure, it is important in practice to verify that Frame Acquisition is indeed not a factor in the BER measurement (and at the same time insure that Frame Acquisition is indeed robust) by sending large numbers of extremely short frames (only a few bytes after the header) having a relatively low E_b/N_0.

MEASURING BER DIRECTLY OVER THE AIR.

The genesis of the entire discussion on the issue of representing BER via FER was the absolute need for Conformance Testing to be done over the air, as opposed to separating the antenna from the remainder of the node and wiring same to test equipment. It was assumed out of hand that over-the-air (radiative) testing automatically precludes measuring BER directly. The reason for this "knee jerk" reaction is that in normal operation:

1. BER measurements are normally made by looping raw decoded data back to the transmitting node's host for comparison.
2. The final product node is not designed to pass data to the 'higher layers" (which would normally be used to conduct the tests) unless the frame is error-free.
3. In normal operation, the receiving node has no knowledge of what has been sent, except to the extent it has been correctly received as verified by the CRC.

The key to measuring BER directly over the air is DFT (Design for Testing). In the Test Mode, the Transmitting Node sends a standard (say 3200 bit) frame the required number of times. The Receiving Node compares the decoded bit values with the standard frame values stored in memory and delivers to its host at the end of the Test a count of the total number of correctly received bits.

The "captive" node (one that resides within host equipment such as a printer and cannot be touched at all) can perform its testing by using its own radio link. To test its transmitting capability, it merely sends out standard frames per the last paragraph. To test its receiving capability, it receives frames and checks the results per the last paragraph. When the test is over, it sends the results back over the air to the Test Node instead of to its hard-wired host.

This entire topic will be covered by the Author in more detail in his upcoming submission IEEE P802.11-95/105 "Can all 802.11 Compliance Testing be Performed without Making Physical Contact with the Unit Under Test?"

CONCLUSIONS

1. For P802.11 conformance testing purposes, FER measurements can be made and used to calculate BER.
2. Before making these measurements, a long series of very short transmissions should be sent, just to verify proper operation of the acquisition circuitry. (This requirement could also be added to the Draft Standard.)
3. At least one more point (a BER of 10^{-4}) should be added to the Draft Standard sensitivity requirement.
4. DFT could eliminate the need to determine BER via FER measurements and facilitate the conformance testing of "captive" or well embedded 802.11 nodes.

1. J. McDonald, *Frequency Hop Topics from January 1995*, IEEE P802.11-95/25, March, 1995
2. L. Zuckerman, *Generic Automated Compliance Testing Configuration For The 802.11 Wireless LAN Specifications*, IEEE P802.11-95/05, May 1995