Increasing the Modulation Depth of the WWVB Time Code to Improve the Performance of Radio Controlled Clocks

John P. Lowe*
lowe@boulder.nist.gov
National Institute of Standards and Technology (NIST)
325 Broadway
Boulder, CO. 80305

Ken C. Allen*
National Telecommunications and Information Administration (NTIA)
325 Broadway
Boulder, CO. 80305

Abstract

The National Institute of Standards and Technology radio station WWVB has officially changed its broadcast format. As of January 1, 2006 the WWVB broadcast signal has increased the depth of the time code modulation from 10 dB to 17 dB. The increase in modulation depth has been implemented to improve the performance of commercial radio controlled clocks in areas of low signal strength. The increase in modulation depth effectively appears to a matched-filter receiver as if the transmitted power has increased by 2.0 dB, thus extending the coverage area over which WWVB controlled clocks will work properly. This is demonstrated by an amplitude shift keyed (ASK) analysis. The results given by this analysis do not depend on the noise level or the bit error rate (BER).

Introduction

The Time and Frequency Division of the National Institute of Standards and Technology (NIST) operates a low frequency radio signal broadcast at 60 kHz from radio station WWVB located near Fort Collins, Colorado. The station went on the air on July 5, 1963, broadcasting a standard carrier frequency. On July 1, 1965 a binary coded decimal (BCD) time code was added to the broadcast containing the day of year, hour, minute, second, and flags that indicate the status of leap years, leap seconds, and Daylight Saving Time [1]. Although WWVB is used by some calibration laboratories as a frequency reference, the primary function of the station is to distribute a time code and provide time-of-day synchronization to low-cost radio controlled clocks. Millions of WWVB controlled wall clocks, desk clocks, and wristwatches are in everyday use in the United States, and millions more are being sold annually.

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Because so many Americans depend upon WWVB controlled clocks as an accurate source of time, NIST is continually seeking ways to improve the readability and reliability of the time code, making the signal easier to receive. One obvious approach to improving time code readability is to increase the station power, as was done in 1999 when the station was upgraded to its current radiated power level of 50 kW [2]. This paper describes another approach to increasing time code readability by increasing the modulation depth of the WWVB signal.

WWVB Modulation and Time Code Format

The WWVB time code is synchronized with the 60 kHz carrier and is broadcast continuously at a rate of 1 bit per second by use of pulse width modulation. The time code bits are produced by amplitude shift keying (ASK) of the carrier, where the carrier power is reduced at the beginning of each second and then restored to full power after a predefined interval. If full power is restored after an interval of 200 ms, it represents a binary '0'; if full power is restored after 500 ms, it represents a binary '1'. A frame marker is sent by holding the carrier low for 800 ms. A binary coded decimal (BCD) format is used, where four binary digits (bits) are combined to represent a decimal number. The complete time code format is shown in Figure 1.

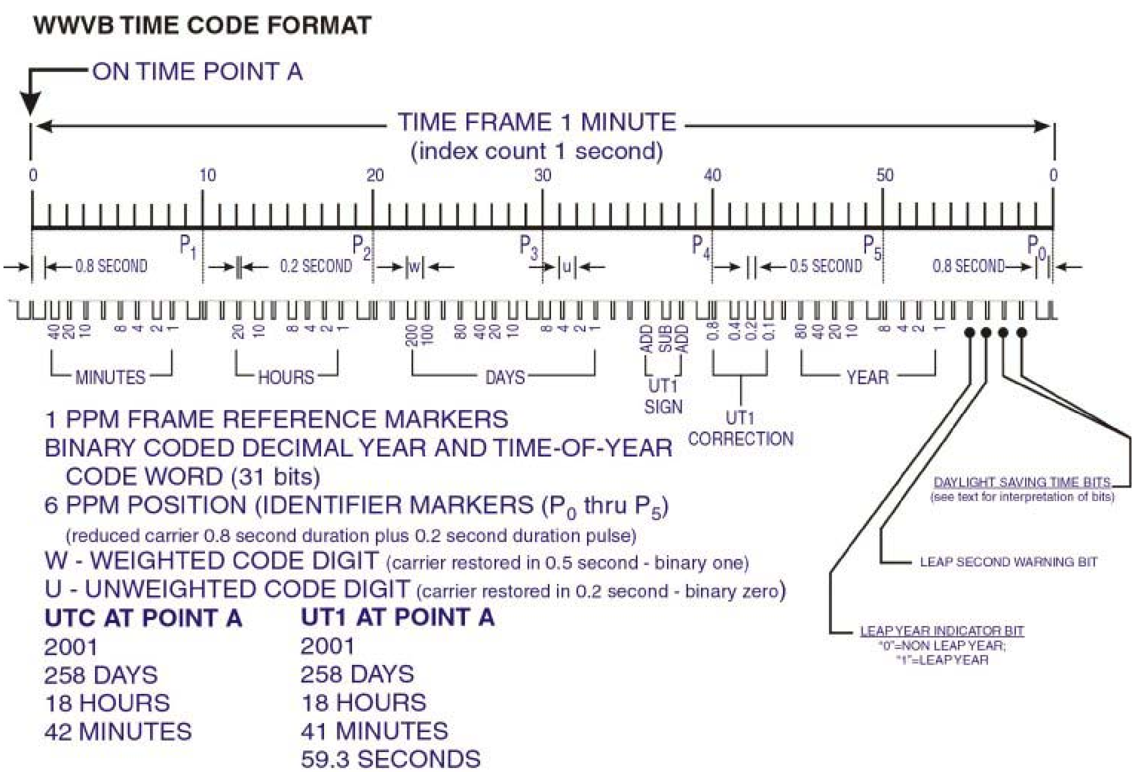

Figure 1. Time Code Format for WWVB.

Since the implementation of the time code in 1965, carrier power was reduced by 10 dB at the start of each second. However, experiments that began in 2005 increased this modulation depth to make the time code bits easier for low-cost radio controlled clocks to decode. The reason for investigating a code modulation change was prompted by a suggestion from a major manufacturer of radio controlled clocks. These experiments consisted of operating several days at a time at different modulation depths. Several different receivers were located on the east coast of the United States and their code reception capability was recorded during these periods. As a result of these experiments (and the analysis that follows), the modulation depth was officially changed from 10dB to 17 dB on January 1, 2006. The increase in modulation depth effectively appears to a matched-filter receiver as if the transmitted power has increased by 2.0 dB.

Signal Analysis

As noted previously, the WWVB signal consists of three possible symbols transmitted at a rate of one symbol per second. The symbol for the binary '0' is sent by reducing the carrier amplitude at the beginning of the second, holding it low for 200 ms, followed by 800 ms of full power. The symbol for the binary '1' is sent by reducing the carrier amplitude at the beginning of the second, holding it low for 500 ms, followed by 500 ms of full power. Frame markers are sent by reducing the carrier amplitude at the beginning of the second, holding it low for 800 ms, followed by 200 ms of full power. A frame marker is transmitted at seconds 9, 19, 29, 39, 49 and 59 of each minute. The double frame marker at the seconds 59 and 0 marks the start of a minute.

The symbol sent thus depends only on the signal level transmitted in two consecutive 300 ms time intervals within each second. This code is presented in Table 1. The code is equivalent to a binary, amplitude shift keyed (ASK) modulation signal. The relative performance of a binary ASK, matched-filter receiver operating in a noise environment is a function of the size of the signal amplitude shift [3]. A timing symbol is composed of two ASK binary symbols or bits. To successfully detect a timing symbol, the state for the two time intervals (two bits) must be correctly detected. Therefore, the probability of a symbol being received in error is equal to the probability of making an error in the first time interval or the second time interval or both time intervals. If the probability of an error in the first time interval is p, then the probability of an error in the second time interval is also p, since the modulation is identical in both time intervals. The probability of an error in both time intervals is p^2. Thus, the total probability of making a symbol error is $p + p + p^2$. It is reasonable to assume that we want the probability of a symbol error to be small. Then, for $p \ll 1$, we have $p^2 \ll p$, so that the probability of a symbol error becomes $p + p = 2p$.

We now have the probability of a time symbol error, $2p$, in terms of the probability of a bit error, p, for an Amplitude Shift Keyed binary modulation.

		1st Interval	2nd Interval	
Symbol	0-200 ms	200-500 ms	500-800 ms	800-1000 ms
'0'	-10 dB	0 dB	0 dB	0 dB
'1'	-10 dB	-10 dB	0 dB	0 dB
frame marker	-10 dB	-10 dB	-10 dB	0 dB

Table 1. Signal Codes (original modulation depth)

Detection

One of two data symbols will be received. The ASK symbol '0' is sent with signal amplitude X_0. The ASK symbol '1' is sent with signal amplitude of $X_1 = C X_0$. The value of C is given by

$$C = 10^{-X/20}. \qquad (1)$$

Where $\boldsymbol{X} = 20 \log_{10}(X_0 - X_1)$ is equal to the amplitude shift in dB.

In the standard digital receiver* the symbol energy (s) is integrated over a symbol duration [4]. The received noise (n) is also integrated over the same symbol duration. The resulting value, $s + n$, has a mean equal to the integrated signal plus a random noise term. Since there are two possible symbols that may be sent, the integrated symbol energy may have two possible values, s_0 and s_1. These values must differ by the transmitted amplitude shift of $\boldsymbol{X}$ dB, i.e.,

$$s_1 = C\, s_0. \qquad (2)$$

A value of $s_1 + n$ is developed when the low power level is received and a value of $s_0 + n$ is developed if the high power level is received (Figure 2).

At the receiver, a threshold is used to decide which symbol is received. When $s_0 + n$ is less than the threshold, a false detect occurs and a '1' is mistakenly received. When $s_1 + n$ is greater than the threshold, a false detect also occurs and a '0' is mistakenly received.

* The standard digital receiver design is optimal for reception in additive, white, Gaussian noise (AWGN), which may not be the optimal receiver design for atmospheric noise at 60 kHz.

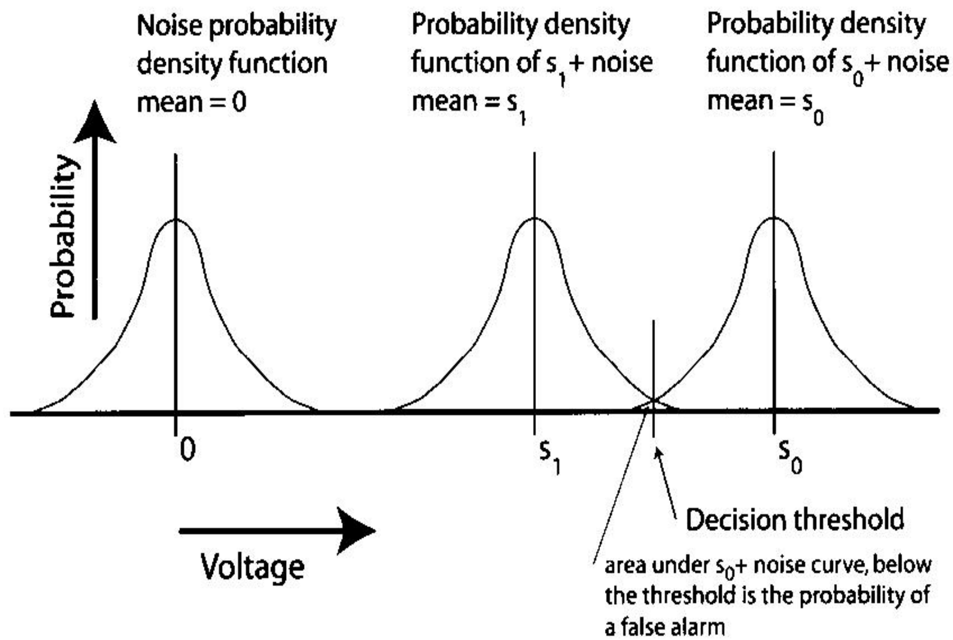

Figure 2. Diagram to determine which ASK bit was sent.

Knowing that the minimum error rate occurs when the probability of false detects are equal, the threshold must be the same distance from s_0 and s_1. The separation between the values of s_0 and s_1 at the receiver determines the bit error rate (BER). We may assume that we require a separation distance of $y = s_0 - s_1$ for a desired BER. We may now solve for the signal level, s_0, necessary for s_0 and s_1 to be separated by y. Using equation (2) we see that

$$s_0 = y / (1 - C). \qquad (3)$$

Now we can find how this required received signal level s_0 depends on the amplitude shift $\boldsymbol{X}$. Say we have two amplitude shifts equal to $\boldsymbol{X_a}$ and $\boldsymbol{X_b}$. Then from equation (3):

$$s_0(\boldsymbol{X_a})/s_0(_\mathbf{b}) = (1 - C_\mathbf{b}) / (1 - C_\mathbf{a}). \qquad (4)$$

If we take 20 $\log_{10}$ of the ratios in equation (4) we will get the difference in dB between the received signal levels required to achieve the same bit error rate. Furthermore, we let $\boldsymbol{X_b}$ be a reference shift amount, say infinity, which corresponds to keying the transmitter on and off. Then we have the signal level increase in dB required to match on-off keying given by

$$s_r(\boldsymbol{X}) = -20 \log_{10}(1 - 10^{-X/20}), \qquad (5)$$

where equation (1) has been used to substitute for C.

Interestingly, the result given in equation (5) does not depend on the noise level or the bit error rate. This means that the improvement in the performance of the receiver, when the amplitude shift, $\boldsymbol{X}$, is increased corresponds to a fixed increase in signal power over the entire area of reception. Comparing the original design modulation depth of 10 dB to on-off keying, or 100 % modulation, gives an effective signal increase of 3.3 dB, i.e.,

$$\mathcal{S}_{\mathbf{r}}\,(10\text{ dB}) - \mathcal{S}_{\mathbf{r}}\,(\infty\text{ dB}) =$$

$$3.3\text{ dB} - 0\text{ dB} = 3.3\text{ dB}.$$

Of course if 100 % modulation depth were implemented there would be no low power carrier signal. The traceable frequency information would be lost during low power periods, and carrier phase tracking receivers would come unlocked.

Figure 3 shows the equivalent loss in signal level when an amplitude shift of ***X*** dB is used instead of on-off keying (100 % modulation) for binary ASK modulation. A 10 dB modulation depth corresponds to 3.3 dB equivalent signal level loss, as shown previously.

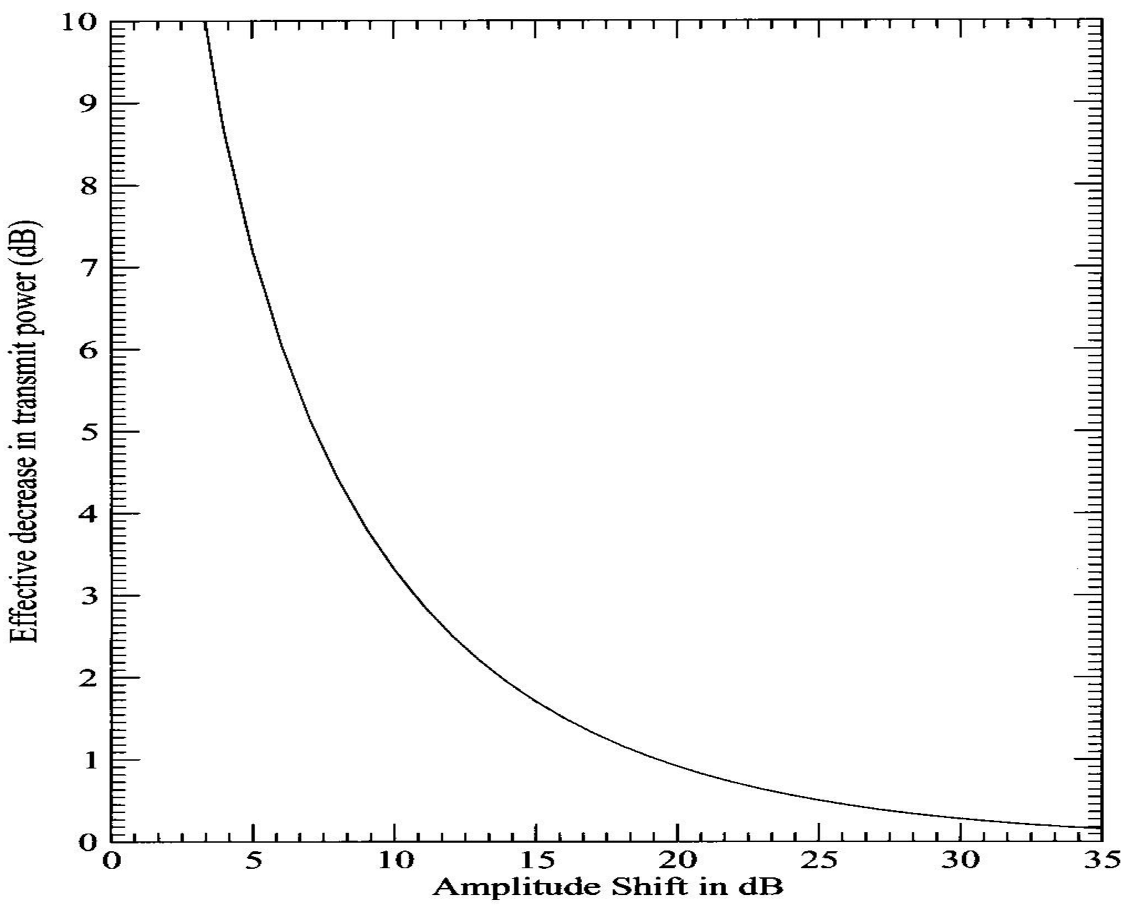

Figure 3. The effective decrease in signal strength measured by a receiver from the optimum level of 100 % modulation (on-off keying) to a modulation depth of ***X*** dB.

Measurements

As mentioned earlier, there is a limit to how much increase in modulation depth is acceptable. Too much reduction in power by amplitude modulation would limit the detection of the carrier frequency. A compromise is required between an increased modulation depth to improve the time-of-day code detection and the maximum low power level amplitude that still allows the continuous detection of the carrier frequency. By experimental tests of receivers located in the eastern United States (some 2000 km from the transmitter), a level of 17 dB modulation depth was determined to be acceptable. This level of modulation depth still allows continuous detection of the carrier frequency under normal propagation conditions.

The effective increase of signal strength as measured by a receiver when the modulation depth is changed from 10 dB to 17 dB can be calculated by Equation (5):

$$\mathcal{S}_r(10\text{ dB}) - \mathcal{S}_r(17\text{ dB}) = 3.3\text{ dB} - 1.3\text{ dB} = 2.0\text{ dB}.$$

Thus, standard digital receivers see the increase from 10 dB to 17 dB of modulation depth as if the transmitter has increased the effective radiated power by 2.0 dB. The radiated power of the WWVB broadcast is measured to be approximately 50 kW. Therefore, with this modification in the modulation format, the readability of the time code has improved to the equivalent of raising the output power to 87kW.

Summary

As of January 1, 2006 the WWVB broadcast has officially changed the modulation format. The depth of the amplitude modulation that determines the BCD time-of-day code has been increased from 10 dB to 17 dB. This modification has improved the decoding capability of radio controlled clocks without significantly degrading the detection of the traceable 60 kHz standard carrier frequency. The increased modulation depth improves the readability of the time code by 2 dB without raising the station's power. Achieving this same effect without increasing the modulation depth would have required increasing the station's radiated power from 50 kW to 87 kW, requiring a significant overhaul of the station's transmission facilities. A minor change in the Time Code Generator was all that was required to achieve the improved performance.

The authors would like to thank the WWVB staff for their dedication and hard work.

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