Time information broadcasting

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The National Institute of Standards and Technology (NIST) operates radio station WWVB, which broadcasts the official time of the United States. The broadcast has emanated from Ft. Collins, Colorado, since 1963, and transmits the year, day, hour, minute, second, other time information, and various indications, using a one-minute-long data frame on a carrier frequency of 60 kHz. Similar broadcasts are in use in other parts of the world, such as in Japan, Germany, and the United Kingdom. *See also:* **Carrier (communications) (/content/carrier-communications/111000)**; **Radio broadcasting (/content/radio-broadcasting/567600)**

Initially, the modulation employed for the encoding of the time information on the WWVB broadcast was limited to pulse-width modulation (PWM) that was realized through amplitude modulation (AM). This allowed for a low-cost implementation of the receiver, which was based on simple envelope detection that was followed by pulse-width measurement. This time code broadcast thus created a commercial industry of radio-controlled clocks (RCCs) and watches that have been selling in high volume. However, the reception and decoding of the AM/PWM code has become increasingly limited by the low signal strength within buildings, which limits the reception of the signal, and by interference from various sources of electromagnetic interference (EMI). These include power supplies, electrical appliances, dimmers for lighting, flat-screen monitors, and other electronic devices that have become more pervasive and may be placed in proximity with the RCC. These reception problems are naturally more severe at longer distances from the station, where greater propagation losses are experienced. *See also:* **Amplitude modulation (/content/amplitude-modulation/030700)**; **Electrical interference (/content/electrical-interference/218800)**; **Pulse modulation (/content/pulse-modulation/556900)**

To address these challenges and allow for more robust reception, in 2012 NIST enhanced the broadcast with a new phase-modulation (PM)–based scheme that retains the legacy AM/PWM format, so that existing devices that receive the broadcast are not impacted. The new phase modulation, which employs binary phase-shift keying (BPSK), benefits from the antipodal distinction between the “1” and “0” data bits, with each of these being represented by an opposite phase (that is, their being 180° apart from one another). This allows receivers that are capable of demodulating the BPSK signal to decode the time information with greater resiliency to noise and interference and therefore operate at much lower signal-to-interference-and-noise ratio (SINR). This article describes this new PM-based broadcast format in detail. *See also:* **Phase modulation (/content/phase-modulation/505800)**

General properties of the phase modulation broadcast signal

The signal properties of the new WWVB broadcast are designed to maintain backwards compatibility with receivers that were designed to operate with the legacy AM broadcast format. These receivers, found in many low-cost RCCs, are typically based on a crystal filter centered at 60 kHz and having a narrow bandwidth, and an envelope detector that detects the drop in the amplitude of the broadcast power that occurs during each second. A digital circuit that follows this envelope detector serves to determine the timing of this amplitude drop, that is, the pulse width, and accordingly determines whether the symbol transmitted was a “0,” a “1,” or a “mark.” Because these properties of the broadcast signal have not been altered with the introduction of the additional phase modulation, the operation of the envelope-detector–based legacy AM/PWM receivers is not affected.

As noted previously, the PM format is based on antipodal BPSK; that is, the two symbols are 180° apart (one is the inverse of the other). A “0” is represented by the carrier's regular phase, whereas a “1” is represented by the phase-inverted carrier. The PM broadcast format was designed to allow for flexibility and scalability, that is, optimized operation at a very wide range of signal-to-noise-ratio (SNR) values, while also making provisions for additional features and extensions. These features allow faster and more accurate synchronization, as well as further address reception, at particularly low signal strength. *See also:* **Signal-to-noise ratio (/content/signal-to-noise-ratio/622200)**

As can be seen in **Fig. 1**, the signal, which combines the two-level legacy AM signal and the phase (sign) inversions, may experience at least four different levels in a phase-modulated frame. These correspond to the legacy AM levels V_H (high voltage) and V_L (low voltage), having the ratio $V_H/V_L \cong 7$, each of which may be multiplied by either a +1, representing a “0” in the BPSK modulation, or −1, for phase reversal, representing a “1” in the BPSK modulation.

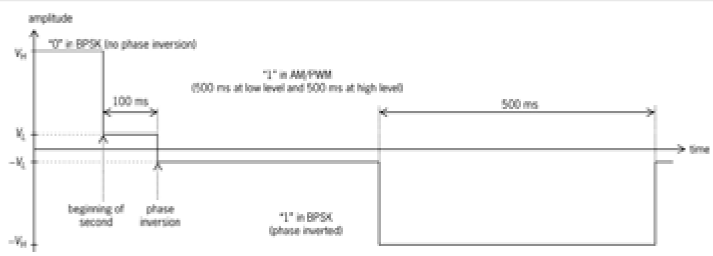

Fig. 1 The baseband signal when a “1” is transmitted both in the legacy format and in the phase-modulation (PM) format. (From J. Lowe, Enhanced WWVB broadcast format, National Institute of Standards and Technology, 2013, http://www.nist.gov/pml/div688/grp40/upload/NIST-Enhanced-WWVB-Broadcast-Format-1_01-2013-11-06.pdf)

The phase transition between each bit and the next one in the 1-bps (bit-per-second) PM frame occurs 100 ms after the AM amplitude drop that indicates the beginning of that second, as shown in **Fig. 1**. This is an example of the baseband version of a transmitted symbol, where the information in the PM is shown to transition from a “0” to “1,” while the transmitted AM/PWM bit is a “1.” The baseband signal shown in this figure is multiplied by the 60-kHz carrier in the transmitter, thereby resulting both in variations in the carrier's amplitude and in sign reversals in it whenever the baseband signal assumes a negative value.

Although the phase representing the information in each symbol is shown to be available after the amplitude in it transitions from V_H to V_L, it is recommended that receivers extract it only from the high-amplitude portion of the symbol. This is not only because of the higher power there, allowing for more robust phase demodulation, but also because the low-amplitude portion may be used in the future for additional (higher-rate) phase modulation.

Figure 2 illustrates an example of the modulated carrier for three consecutive bits representing M, 0, 1 for the legacy AM/PWM signal (M = marker) and, simultaneously, 0, 1, 0 in the phase-modulated data (following a 0 bit). The combined modulating baseband signal, which represents both the information represented in the legacy AM/PWM signal and the additional information incorporated in the phase, is shown by a broken red line. Negative values, resulting in carrier inversion, represent a "1" in the PM data, where the broken red line representing the baseband signal crosses the blue carrier waveform.

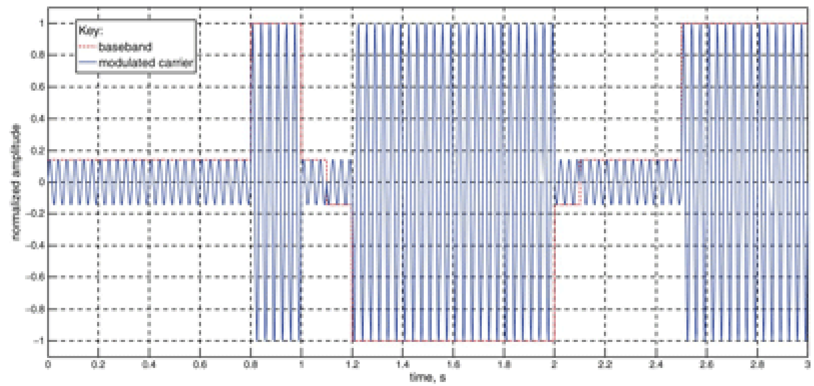

Fig. 2 An example of the broadcast signal for three consecutive bits (M, 0, 1 for the legacy signal; and 0, 1, 0 in the PM data). (From J. Lowe, Enhanced WWVB broadcast format, National Institute of Standards and Technology, 2013, http://www.nist.gov/pml/div688/grp40/upload/NIST-Enhanced-WWVB-Broadcast-Format-1_01-2013-11-06.pdf)

Binary phase-shift keying modulation gain

One way to determine the robustness of a communication system operating in the presence of additive noise is to normalize the modulation signals using a Gram-Schmidt orthogonalization process that then represents the power in a two-dimensional signal space. The legacy WWVB broadcast uses PWM in which the binary symbols "0" and "1" are represented by different full-power durations, as shown in **Fig. 3***a*. Full-power transmission refers to the portion using the maximum transmission power, and the amplitude in full-power duration is normalized to 1. The suppressed duration refers to the portion having a transmission power suppressed to −17 dB with respect to the full power (that is, an amplitude reduction to about 1/7 of the high value). The corresponding normalized signal-space diagram is shown in **Fig. 3***b*. While the normalization ensures the maximum transmission power is 1, the Euclidean distance (d) between the legacy "0" and "1" signals is only 0.52, implying that this modulation scheme is inefficient. *See also:* **Decibel (/content/decibel/182200)**

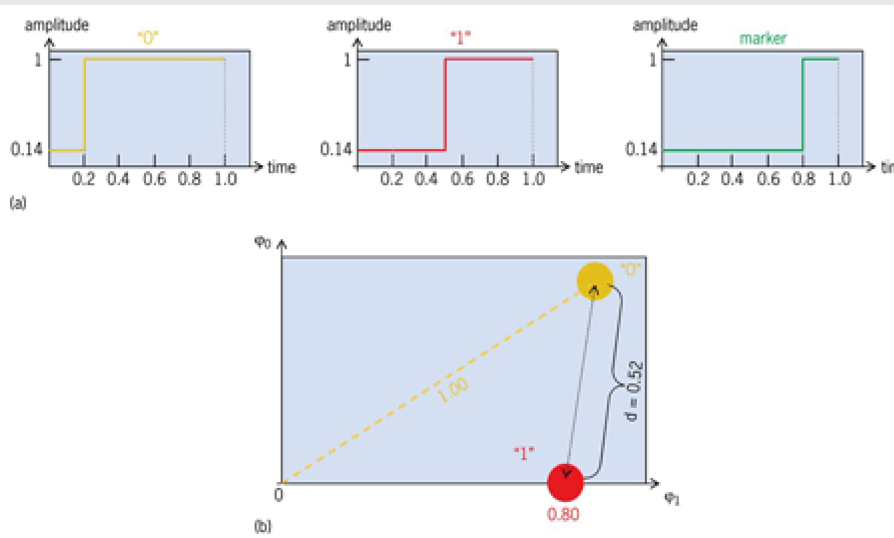

Fig. 3 Waveforms and Euclidean distance for AM-based legacy broadcast format. (*a*) Baseband waveforms of the WWVB legacy broadcast format. (*b*) Signal-space representation of the legacy broadcast format. (After Y. Liang et al., 2014)

As noted previously, the PM scheme uses antipodal BPSK, in which a binary “0” is represented by maintaining the carrier phase, and a binary “1” is represented by inverting the carrier (that is, 180° phase shift). **Figure 4***a* shows the four possible baseband waveforms for the various combinations of AM/PWM- and PM-based information symbols. As seen in **Fig. 4***b*, the corresponding minimum Euclidean distance in PM (*d*') is about three times greater than that of the legacy format (*d*), resulting in a performance gain of $20 \times \log_{10}(3) \approx 10$ dB, when it is assumed that both schemes are received in an optimal coherent receiver. This implies that the PM format, despite not altering the signal's power, allows the information on the noisy received signal to be recovered with the same reliability (that is, probability of bit errors) when the SNR is 10 dB lower. It should be noted, however, that typical legacy receivers are based on envelope detection, as noted previously, so the actual performances difference is even greater than 10 dB. Further, the inherently higher immunity of a BPSK receiver to interference, and particularly to an on-frequency, nonmodulated, continuous waveform, allows the PM-based receiver to withstand higher levels of interference than those that may be tolerated in a legacy envelope-detector receiver.

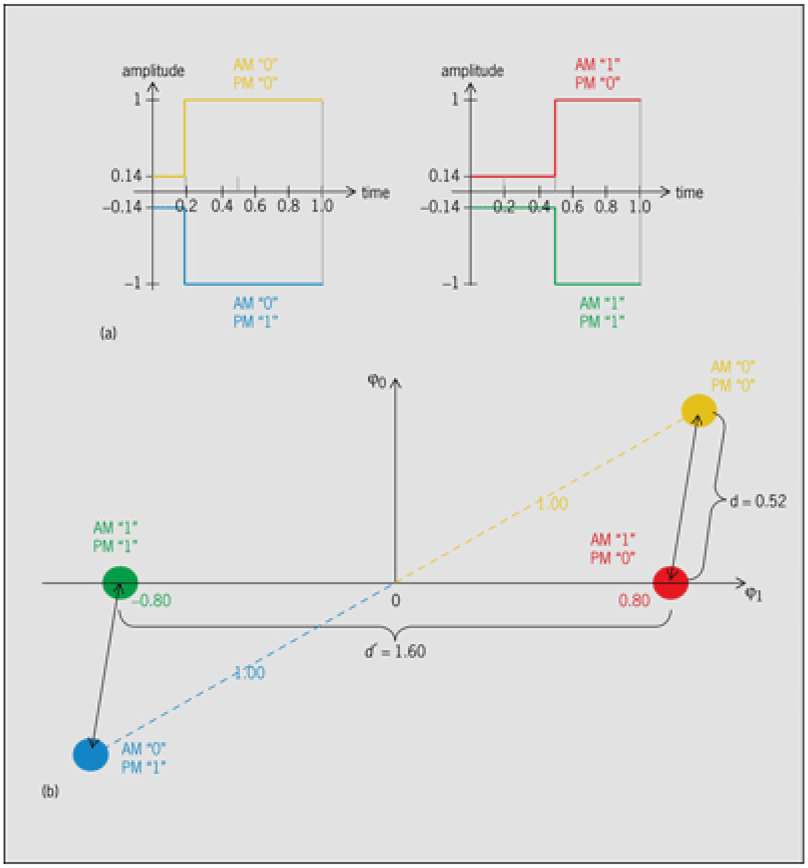

Fig. 4 Waveform and Euclidean distance comparison of legacy (AM/PWM) and PM-based signals. (*a*) Baseband waveform of the WWVB transmitted signals. (*b*) Signal-space representation of the legacy and PM-based modulations. (After Y. Liang et al., 2014)

In addition to its improved modulation scheme, the new broadcast format also offers more efficient data representation. The minute, hour, day, and year fields are all combined into one 26-bit field that represents the number of minutes that have elapsed since the beginning of the year 2000. A repeated bit and a 5-bit parity word, derived from a Hamming linear-block code for error correction and detection, are added, totaling 32 bits for the time representation. This number of bits is, coincidently, identical to the number used for the time and date representation in the legacy format as well, but without the level of protection offered by the new scheme. This Hamming code is capable of correcting one erroneous bit and detecting up to two bit errors, and thus increases the robustness of the reception. The decoding operations performed in the receiver involve an error-detection calculation, as well as conversion of the minute counter into the actual date and time. The new format also eliminates the astronomical time error information (UT1), which consumes 7 bits in the legacy format and is not of much use in RCCs, as well as the leap-year indication bit, which is redundant when the year is known.

Time-frame structure

Table 1 lists the five different fields in a time frame, which add up to 60 s in duration. The new frame structure, shown in **Table 2**, is designed to improve the robustness of information recovery and reduce the overall energy consumption associated with reception. The markers at the 1-, 10-, 20-, 30-, 40-, 50-, and 60-s marks in the legacy frame, denoted by M in **Table 2**, are used only for frame synchronization in legacy receivers, and separate the minute, hour, and day information. The duration of the high power level in markers, as defined by the legacy broadcast format, is only 200 ms (compared to 500 and 800 ms for the "1" and "0" symbols, respectively). Because of this lower energy content, the marker bits generally were not assigned information bits in the new PM-based frame. (There is one exception to this rule: The marker at the 20-s mark is assigned to a bit in the Time and Date field of the PM frame, but this assignment is permissible because the PM bit in question just duplicates the bit in the PM frame at the 47-s mark). The leap-second notification and daylight saving time (DST) current state are merged into a 5-bit code word in the new format, denoted by D + L. The schedule for the next DST transition is represented by a 6-bit code word in the DST Next field of the new format. The synchronization word allows rapid synchronizing to the start of the minute without having to decode the entire minute frame. If a receiving device has already been set to the correct time (decoded the signal earlier), it can reduce most of its subsequent receptions to just the synchronization word at the beginning of a frame and resync based on the received timing of that word, thus saving time and energy that would be required for the reception of an entire 60-s frame. Such reception is also more robust, because it requires only the identification of a short known sequence within a time window that is limited according to the timing drift that the RCC is attempting to correct, rather than having to recover an entire 60-bit frame in the presence of timing uncertainty.
See also: **Coordinated Universal Time (UTC) scale (/content/coordinated-universal-time-utc-scale/YB110155)**; **Time (/content/time/697400)**

Table 1 - List of fields in a 1-min time frame

	Purpose of field	Bits allocated	Total number of bits (and seconds in duration)
1	Synchronization word (may include last bit of previous frame)	1–13, 60	14
2	Time word [includes 5 parity bits (14–18) and repeated least significant bit]	14–29, 31–39, 41–47	32
3	Daylight saving time (DST) state and leap-second notification	48–49, 51–53	5
4	Advance notice for next DST transition (or message word)	54–59	6
5	Reserved bits	30, 40, 50	3
		Total:	**60**

TABLE 2. Frame structure of AM/PWM (amplitude/pulse-width modulation) and PM (phase modulation) information symbols*

Bit index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
AM/PWM	M	Minute			R	Minute				M	R	R	Hour		R	Hour				M	R	R	Day		R	Day				M
PM	Sync word													Time and Date																R

Bit index	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
AM/PWM	Day				R	R	UTI			M	UTI				R	Year				M	Year				R	LY	LS	DST		M
PM	Time and Date									R	Time and Date							D + L		R	D + L			DST Next						0

*M denotes marker, R denotes reserved, D + L denotes DST state and leap second, LY denotes leap year, LS denotes leap second. The "0" at the end of the frame may be regarded as the first bit of the synchronization word (Sync word).

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Links to Primary Literature

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Additional Readings

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