WWVB Time Signal Broadcast: An Enhanced Broadcast Format and Multi-Mode Receiver

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Abstract

WWVB is a broadcast station, operated by the National Institute of Standards and Technology, which has been broadcasting time information to radio-controlled clocks (RCC) throughout the continental US since 1965. The transmitted information includes the year (excluding the century), day, hour, minute, and notifications for leap seconds and for daylight saving time (DST) transitions. By receiving this information from WWVB, RCCs can acquire and maintain accurate timing and automatically adjust for DST transitions and leap seconds. The legacy amplitude modulation (AM)-based broadcast format, introduced in the 1960s, while allowing for a simple implementation of a receiver with the technology of that era, exhibits low efficiency. Consequently, RCCs based on it often fail to receive reliably, particularly in locations that are distant from the station, such as on the East Coast. To improve the station's coverage, an enhanced broadcast format, based on the addition of phase modulation (PM), was deployed in 2012. This article presents an overview of this new broadcast format and its enhanced features, including its modulation scheme, information encoding, channel coding, and transmission modes. These features enable more reliable receiver performance and greater time-keeping accuracy at reduced power consumption. Additionally, various challenges and considerations associated with the design of receivers for the new broadcast format are presented.

I. WWVB AND THE LEGACY AM/PWM-BASED BROADCAST FORMAT

WWVB is a time-signal broadcast station located near Fort Collins, Colorado, operated by the National Institute of Standards and Technology (NIST). WWVB continuously broadcasts digitally represented time information that is derived from an accurate atomic-clock signal source. The time information in the broadcast includes the date and time, as well as notifications related to upcoming daylight saving time (DST) transitions and leap seconds [1]. The broadcast may also carry short messages, such as emergency alerts. WWVB transmits in the Low-Frequency (LF) band at 60 kHz with an effective radiated power of 70 kW, allowing propagation to great distances, particularly during the night, when the conditions

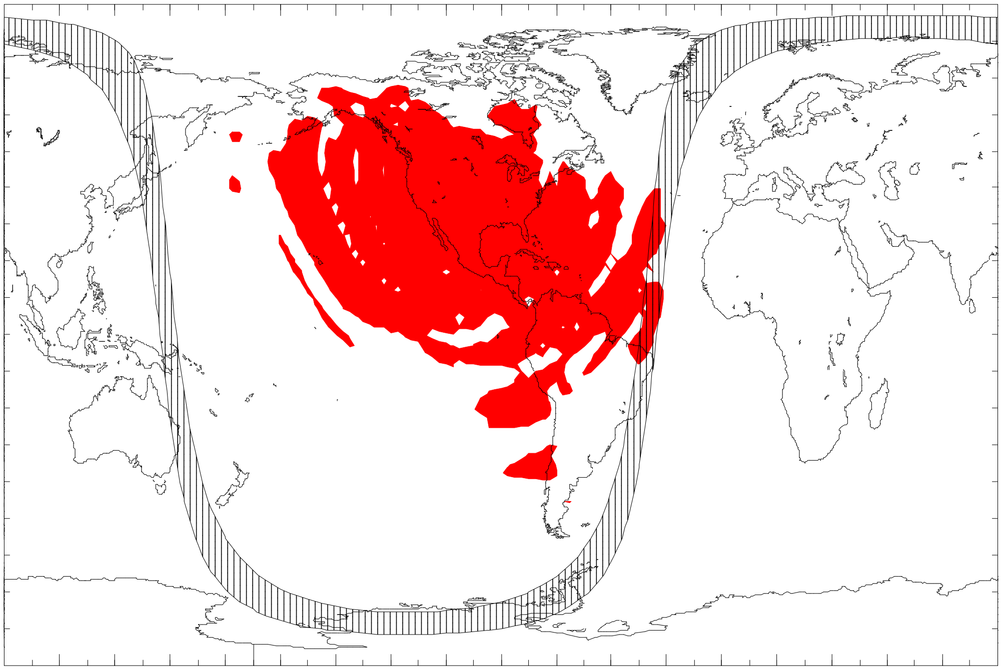


Figure 1. Simulated coverage area for the legacy WWVB broadcast at 0800 UTC (Coordinated Universal Time) in October, where the shaded area is the day-night boundary. The simulated coverage assumes the use of a properly oriented antenna and the absence of interference and shielding losses. These three assumptions are often invalid in indoor applications.

of the ionosphere are favorable. Millions of radio-controlled clocks (RCCs) throughout North America, commonly known as ‘atomic clocks’, periodically synchronize to the station for accurate time-keeping.

The legacy WWVB broadcast format, developed in the 1960s, was designed to enable low-cost envelope detection-based receivers, similar to those that were widely used for AM audio broadcasting reception. The amount of information transmitted by WWVB is less than 50 bits each minute at a bit rate of 1 bit per second, occupying a bandwidth of a few hertz [2]. WWVB transmits 24 hours a day and every frame aligns with the start of a minute, enabling the seconds to be extracted based on the frame boundaries.

Figure 1 shows the simulated coverage area of the WWVB legacy broadcast at night, during which time the reduced absorption in the ionosphere allows for optimal propagation. The simulated coverage area assumes that a RCC will receive successfully if the field intensity exceeds 100μV/m. This assumption is valid for a typical commercial RCC having a ferrite-rod antenna that is oriented correctly towards Fort Collins [3]. It does not account for possible interference experienced in the receiver or for additional propagation (shielding) losses that may be experienced indoors.

However, these assumptions are often invalid. First, the receiver’s antenna is likely to be oriented randomly, potentially at an orientation for which it experiences a low gain in the direction of the broadcast. Second, man-made noise and radio-frequency interference are likely to be present and dominate the receiver performance. Third, the signal may experience shielding losses, representing a major challenge, particularly in large buildings.

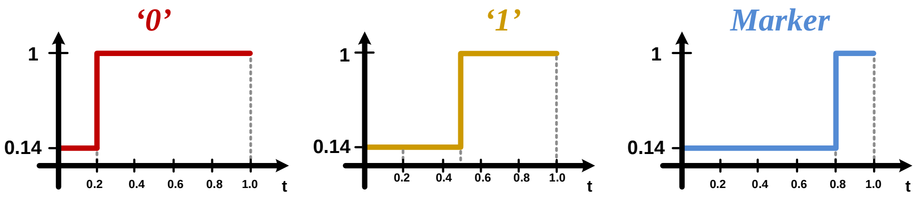
Consequently, many RCCs, based on the legacy broadcast format, experience reception failures despite being located within the coverage area shown in Fig. 1. This unreliability has impeded the use of RCC solutions in many applications, such as digital cameras and microwave ovens [4].

The legacy WWVB broadcast uses pulse-width modulation (PWM) in which the binary symbols ‘0’ and ‘1’ are represented by different full-power durations, as shown in Fig. 2(a) [3]. Full-power transmission refers to the portion using maximum transmission power, and the amplitude in full-power duration is normalized to 1 in Fig. 2(a). The suppressed duration refers to the portion having a transmission power suppressed to -17 dB with respect to the full power. The corresponding constellation diagram is shown in Fig. 2(b), where Φ_1 is the normalized waveform of ‘1’ in AM, and Φ_0 is the orthogonal basis function that is derived using the Gram-Schmidt orthogonalization process to span the two-dimensional signal space. While the normalization ensures the maximum transmission power is 1, the Euclidean distance between the legacy ‘0’ and ‘1’ signals is only 0.52, implying that this modulation scheme is inefficient. The data representation in the legacy format is also inefficient, as it is based on binary coded decimal (BCD) representations for each decimal digit. Due to these inefficiencies in the legacy broadcast format, and to overcome the reception challenges mentioned above, NIST decided to develop a new broadcast format that would allow for reliable and cost-effective reception throughout the continental United States.

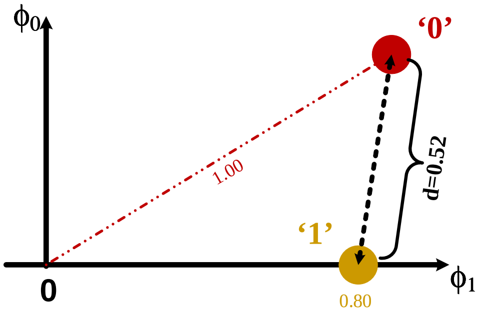
Several other countries operate radio time-signal stations similar to WWVB (e.g., DCF-77 in Germany, MSF in England and JJY in Japan) [5]–[7]. These transmitters operate in the range 40 to 80 kHz, with the same bit rate and frame length as WWVB. Although these stations use modulation schemes similar to that of the legacy WWVB format to represent the time information, the signal broadcast from DCF-77 also includes portions that are phase-modulated by a higher-rate pseudo-random sequence. This higher-rate PM component allows time-keeping equipment to achieve higher accuracy while being robust to interference [5].

II. THE NEW PM-BASED WWVB BROADCAST FORMAT AND ITS FEATURES

NIST officially commenced transmission of the new phase-modulation (PM)-based broadcast format on October 29, 2012, while maintaining the AM/PWM based modulation of the legacy format. The phase modulation added to the broadcast was designed such that it would not affect the operation and performance of existing commercial RCCs whose operation is based on envelope detection, thus maintaining backward



(a) Baseband waveforms of the WWVB legacy broadcast format



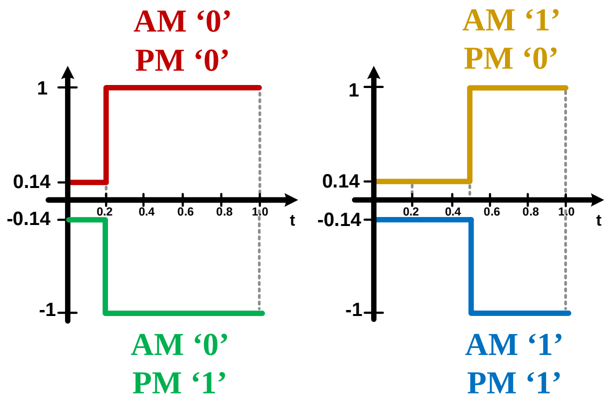
(b) Signal space representation of the legacy broadcast format

Figure 2. Waveforms and Euclidean distance for AM-based legacy broadcast format

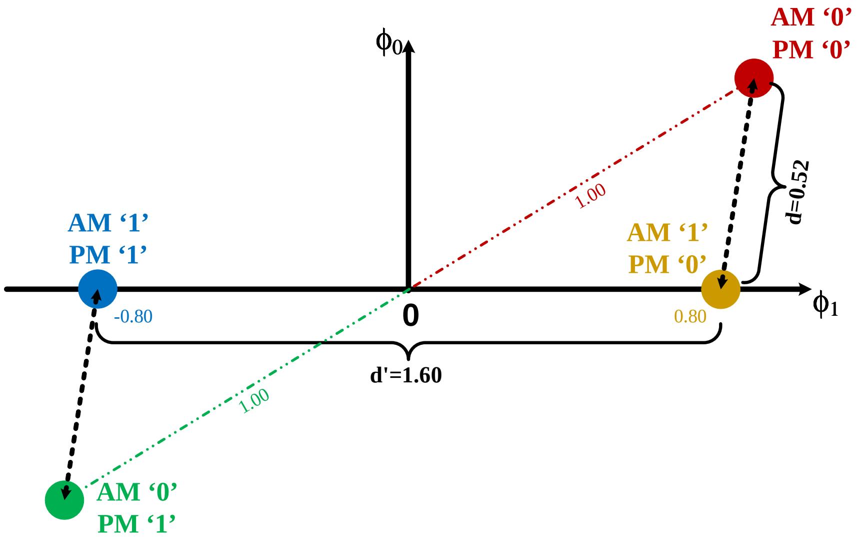
compatibility. Reception equipment based on carrier locking, either for synchronous AM detection of the time information or for extraction of the carrier as a frequency reference source, may be adapted to operate on the phase-modulated signal by employing techniques such as squaring or a Costas loop.

The PM scheme uses antipodal binary phase-shift keying (BPSK), in which a binary '0' is represented by maintaining the carrier phase, and a binary '1' is represented by inverting the carrier (*i.e.* 180° phase shift). Figure 3(a) shows the four possible baseband waveforms for the various combinations of AM and PM-based information symbols. As seen in Fig. 3(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 assuming that both schemes are received in an optimal coherent receiver. It should be noted, however, that typical legacy receivers are based on envelope detection, such that the difference is greater than 10 dB. Further, the inherently higher immunity of a BPSK receiver to interference, and particularly to an on-frequency non-modulated 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 [3].

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 '00. A 5-bit parity word, derived



(a) Baseband waveform of the WWVB transmitted signals

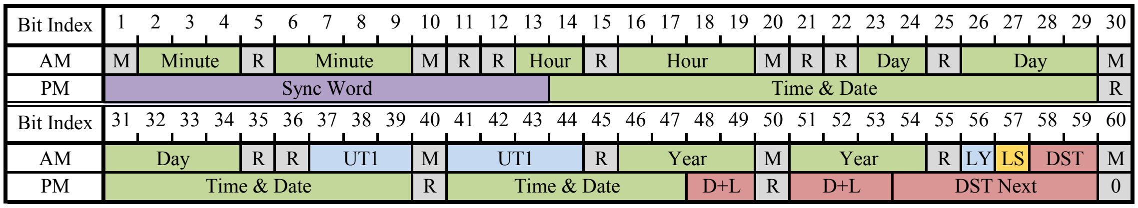


(b) Signal space representation of the legacy and PM-based modulations

Figure 3. Waveform and Euclidean distance comparison of legacy (AM) and PM-based signals

from a Hamming (31,26) linear-block code for error correction and detection, is added, totaling 31 bits for the time representation. This number of bits is, coincidently, identical to that 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, involving a syndrome calculation, as well as the conversion of the minute counter into the actual date and time, are relatively simple operations in a modern implementation. The new format also eliminates the astronomical time error information (UT1), which consumes seven 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.

The new broadcast format supports the following transmission modes, having different code rates, to accommodate various ranges of receiver signal-to-noise ratio (SNR):



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	M	Minute			R	Minute				M	R	R	Hour		R	Hour				M	R	R	Day		R	Day				M
PM	Sync Word													Time & 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	Day				R	R	UT1			M	UT1				R	Year				M	Year				R	LY	LS	DST		M
PM	Time & Date									R	Time & Date							D+L		R	D+L			DST Next						0

Figure 4. Frame structure of AM (Amplitude Modulation) and PM (Phase Modulation) in Normal mode, where *M* denotes marker, *R* denotes reserved, *D+L* denotes DST state and leap second, *LY* denotes leap year, and *LS* denotes leap second.

- *Normal mode*, which has the same frame duration of one minute and bit rate of 1 bit/s as in the legacy format, includes information similar to that of a legacy AM frame, as shown in Fig. 4.
- *Message mode*, which also has the same frame length and bit rate as the legacy AM-based format, contains no time information, but can convey other types of information, such as emergency alerts and control commands.
- *Fast mode*, which has a much faster bit rate and shorter frame duration than the Normal mode, requires a shorter reception time and lower processing energy, while including all the information of Normal mode.
- *Medium mode*, which targets receivers that experience very low SNR by using frames of 6 minute duration every half hour, conveys only the time and DST state.
- *Long mode*, which is designed to accommodate reception under even lower SNR conditions than the Medium mode, uses 17 minute frames that are transmitted once a day. The time of day information can be derived from the frame's timing, and two separate dedicated Long frames, broadcast at designated times of day, represent the DST state and date, respectively.

The following subsections provide additional details for these transmission modes.

A. *The Normal Mode*

The new frame structure, shown in Fig. 4, is designed to improve the robustness of information recovery and reduce the overall energy consumption associated with reception. The markers in the legacy frame, denoted by *M* in Fig. 4, are used only for frame synchronization in legacy receivers. Due to their lower energy content, these were not assigned information bits in the new PM-based frame. The leap-second notification and DST current state are merged into a 5-bit codeword in the new format, denoted by *D+L*. The schedule for the next DST transition is represented by a 6-bit codeword in the *DST Next* field of the new format.

TABLE I

COMPARISON OF THE DIFFERENT RECEIVER OPERATIONS IN NORMAL MODE

RX Operation	Frequency of Operation	A-priori knowledge	Purpose	Reception duration	Information to be recovered
Acquisition	When batteries are replaced	None	Acquire time information	2 min	FS timing, Time & date, DST state
Tracking	Daily	Approximate time	Compensate for time drift	14 s + t_m	FS timing
Notification Reception	Twice a year	Approximate time	Obtain DST schedule and LS notification	1 min + t_m	FS timing, DST schedule and LS notification

Different receiver operations enabled — There are three receiver operations for RCCs whose reception is based on the Normal frame. First, when a radio-controlled clock is new or reset, it will perform *acquisition* to synchronize with WWVB and obtain the current time, date, and additional information in the frame. Subsequently, after successful acquisition, the device periodically performs *tracking* to compensate for the time drift in its internal oscillator. A common commercial RCC may have to compensate for up to a few seconds of time drift, if its periodic tracking operations are performed once a day. Note that the propagation delay in the continental US is less than 15 ms [8], and hence the time drift is dominated by the frequency error of the RCC's crystal rather than the geographic location of the receiver. The tracking operation is based on the reception of the synchronization word (or sync word), from which the correct timing is derived, and does not include reception of information. A third operation, *notification reception*, is used to obtain information regarding the schedule for the next DST transition and the possible implementation of a leap second. The different receiver operating modes are compared in Table I, wherein the time and date information includes minute, hour, date, and DST state, FS timing represents frame and symbol timing, and t_m represents the maximal time drift to be compensated.

Most legacy RCCs perform acquisition daily, requiring that at least one full 60-second frame be received successfully each time. By contrast, the tracking operation offers energy consumption reductions due to its shorter operation duration, as well as greater chances of being successful [9]. The notification-reception operation involves the extraction of fewer information bits from the received signal, when compared to the acquisition operation, and is done when the timing (*i.e.*, minute boundaries) is known.

Sync Word for Synchronization — The new broadcast format uses a 13-bit sync word with good auto-correlation properties to enable robust FS synchronization at the receiver. The last PM bit in each frame, coinciding with the marker at second 59 of the legacy frame, is fixed at zero and may be considered an additional bit in the sync word, extending the sync word to 14 bits. Since the duration of this word is shorter than a quarter of the frame, and its approximate timing is known when the RCC is tracking (rather than acquiring), the duration and energy consumption of the tracking operation are correspondingly lower. Although the sync word is also used in the acquisition operation, to determine the start time of the frame, the sync word design was based primarily on performance metrics associated with the tracking operation. The reasons for this are: (i) tracking is the most frequent operation in the RCCs, and (ii) the false synchronization probability in acquisition can be reduced by leveraging the channel-coding schemes employed in the data in order to verify the validity of the various fields in the frame. The bits in the sync word may have three different levels of energy, depending on whether they are accompanying a ‘0’, ‘1’ or marker bit in the legacy format. Hence, if a traditional synchronization sequence were chosen, such as the Barker code, it may not have exhibited its known auto-correlation properties, thus resulting in inferior performance. Therefore, the sync word was designed to maximize the reliability of the tracking operation by treating the sync word as a waveform rather than a sequence of bits.

Emphasis on Daylight Saving Time — DST is observed throughout most of the US, and automatically adjusting the time when DST transitions occur is considered one of the most significant benefits of RCCs. Hence, in the new broadcast format, a new 6-bit field was introduced, *DST Next*, consuming 10 % of the entire 60-second frame, intended primarily to convey the schedule for the next DST transition. Additionally, a 5-bit field conveys both the current DST state and a leap second notification for the end of the current month. There are four possible DST states: *DST in effect for more than a day* (*i.e.*, within summer time); *DST not in effect for more than a day* (*i.e.*, within winter time); *DST starting today*; or *DST ending today* [1]. There are three possible leap-second notifications: *no leap second this month*, or a *positive* or *negative leap second to occur at the end of this month* [1]. Leap seconds are usually not scheduled for at least ten months in a year, and DST is in effect for about $\frac{2}{3}$ of the year. Therefore, to increase the overall probability of successful decoding, given the unequal probabilities for the different codewords, the codeword representing DST in effect for more than a day and no leap second was chosen to have the largest minimum distance (d_{min}) in the codebook. Over the last decade, the implementation of leap seconds has been discussed internationally and it has been suggested that leap seconds be abolished altogether [10]. The 5-bit error correction code was therefore designed such that if leap seconds are eventually abolished, it will become a systematic block code, with the most commonly used codewords for DST (summertime and wintertime) having the maximum d_{min}.

The 6-bit *DST Next* field in Fig. 4 informs the RCCs of the next DST transition well ahead of time, eliminating the criticality of decoding the DST-state field daily. There are 24 possible upcoming DST transition schedules for both the beginning and the end of the DST period. When transitioning into DST (in March or April), an advance notification of about seven months is provided for the ending of the DST period (to occur in October or November), whereas at the end of a DST period, an advance notification of about five months is provided for the beginning of next year's DST period. The 24 combinations represented by the 6-bit codewords cover eight different Sundays and three different times for implementing the transition: 1 a.m., 2 a.m., or 3 a.m. [1]. Additional codewords serve to represent possibilities such as a DST transition occurring outside of those 24 possibilities [1]. As with the 5-bit codeword for the DST state and leap second notification, the most probable DST transition schedules were chosen to have the greatest d_{min}.

B. Additional Transmission Modes

Due to the diverse locations and environments where receivers may operate, different transmission modes were designed to accommodate the wide range of receiver SNRs and impulse noise scenarios.

The Fast mode, which has not yet been deployed, will allow high SNR users to have shorter reception duration and thus minimizes energy consumption. A Fast frame is transmitted at a bit rate of 100 bit/sec during the suppressed duration of a marker bit, and can therefore be transmitted simultaneously with a frame from any other mode. The Fast mode may also be considered an effective solution against impulse noise, assuming that the reception of a Fast frame, having a duration of less than one second, occurs at an instance in which sufficiently high SNR is experienced.

While the Fast mode is intended for RCCs having higher SNRs, the Medium mode is targeted at RCCs that are affected by noise, interference and/or shielding losses to the extent that they cannot operate in Normal mode. In the Medium mode, a 106 bit sync word is used for frame synchronization, surrounded by two mirrored 127-bit PN sequences that are chosen from a set of 124 PN sequences of length 127 bits, representing the current minute, hour and DST state. The Medium frame is transmitted twice every hour at minute 10 and 40 [1].

The Long mode, which has not yet been deployed, is intended for receivers that do not have sufficient SNR to operate in Medium mode. In Long mode, a 1023-bit PN sequence truncated to 1020 bits, is broadcast at a designated time of day. After a certain time gap, a second truncated 1023-bit PN sequence is broadcast, chosen from a set of two truncated 1023-bit PN sequences, to indicate the current DST

TABLE II
COMPARISON OF THE DIFFERENT TRANSMISSION MODES

TX modes	Bit rate	Information represented	Frame duration	Frequency of Occurrence	Minimum RX CNR
Fast	100 bps	Time, Date, DST state, DST schedule, LS notification	630 ms	every 10 s	30 dB
Normal	1 bps	Time, Date, DST state, DST schedule, LS notification	1 min	every 60 s	10 dB
Message	1 bps	Message	1 min	infrequent	10 dB
Medium	1 bps	Minute, Hour and DST state	6 min	every half hour	-3 dB
Long	1 bps	Time, DST state and Date (in separate frames)	17 min	every 24 hours	-13 dB

state. There are also Long frames dedicated to represent the date, which are broadcast at designated times of day. The Long frames are transmitted after midnight in the Continental US for two reasons: i) the propagation conditions are better during the night, and ii) the probability of a RCC performing initial acquisition at such time would be low, thus minimizing the population of RCCs that would be deprived of the opportunity to acquire based on the Normal frames, which are overridden by the Long sequences.

Table II provides an overview of the various transmission modes, where CNR refers to Carrier-to-Noise Ratio in a bandwidth of 1 Hz. The effective SNR is about 2 dB lower on average than the CNR due to the coexisting AM/PWM in the transmitted BPSK symbols. The minimum receiver CNR is defined for reliable recovery of 100% of the frame's content, such that the probability of an error in a recovered frame is about 10^{-4}. Existing RCC receivers based on the legacy format require a minimum receiver CNR of about 28 dB, for which their probability for erroneous recovery is unspecified and is likely higher than 10^{-4}. Hence, receivers based on the new broadcast format have a performance advantage in the range of 18 to 41 dB. The performance advantage in Normal mode has been shown in simulations [11], reception trials and lab testing [9].

III. RECEIVER DESIGN CHALLENGES

There are several unique design considerations for WWVB receivers when compared to conventional communication systems. First, consecutive data frames are highly correlated and, therefore, repeated reception may be employed to ensure reliability. Second, the receiver SNR can vary significantly depending on the reception time, location and interference level, requiring that the receivers be designed to accommodate a wide range of SNR. Third, the broadcast's bit rate is very low, resulting in relatively large frequency offsets that may be experienced during coherent demodulation. Finally, energy consumption must be minimized for battery-operated devices.

A. Multiple Receptions for Increased Robustness

In traditional data communication systems, repeated transmission/reception can result in an undesired decrease in throughput. In contrast, in the WWVB broadcast, apart from the infrequent changes in the DST and LS fields, consecutive frames are strongly correlated, such that successfully decoding one frame is equivalent to recovering data from other frames. Therefore, multiple reception attempts can be made to increase reception robustness without loss of information. The only penalty associated with repeated reception is increased energy consumption and a possible delay in obtaining the result. Except during acquisition, this delay is not noticed by the user, since the devices are mostly in tracking mode, in which their timekeeping continues even without time-drift correction.

Developing a reliable metric for reception quality is essential to determine the need for a second reception attempt. Estimated CNR/SNR is an example of such metric. The syndromes in acquisition operations, derived from the error-correcting codes employed in the data, can also indicate the reception quality, as long as the number of errors does not exceed the detection capability of the channel code.

B. Receiving at the Different TX Modes

The receiver can operate over a wide range of SNR values and leverage the multiple different modes provided by the enhanced broadcast. Therefore, a reliable quality measure and decision strategy are required to determine which transmission mode would guarantee robust reception for a particular RCC under specific SNR conditions, while also considering response time and energy consumption. While lower SNRs generally require the use of lower code rates, as offered by the Medium or Long modes, interference of impulsive nature may be effectively addressed by the Fast mode, where the entire frame may be received in less than one second, allowing for greater chances of it not being impacted. Note that since reception conditions may vary, a device forced to acquire using the Medium mode, for example (possibly during daytime reception and in the presence of interference), may perform periodic tracking based on the Normal or even Fast modes at night, when the received signal is stronger and the interference levels may be lower.

C. Compensating for Time-Varying Frequency Offsets in the Coherent Receiver

Although the 60 kHz carrier generated by the station is accurate, the low-cost crystals used in most RCCs result in a time-varying frequency offset between the transmitter and receiver. Major factors that affect the frequency accuracy of a crystal include temperature, crystal aging, and retrace [12]. The relative frequency tolerance of crystals in commonly used clocks and watches is up to 20 ppm, which translates into 1.2 Hz for a 60 kHz local oscillator for frequency down-conversion. Depending on the frequency error, the phase error accumulated throughout the coherent demodulation of a symbol may be intolerable due to the long symbol period for most transmission modes. Therefore, the frequency offset must be compensated during synchronization and data recovery.

Further, since the reception time period is on the order of minutes, certain environmental changes (such as temperature) may occur during that period of time, which can affect the crystal frequency. In an experiment performed in an air-conditioned lab, where the temperature fluctuations are much smaller than those in outdoor environments, the frequency fluctuations were on the order of 0.01 Hz within a minute. In Long mode, where the timing and information recovery is made based on a 17-minute sequence, frequency fluctuations of such magnitude can be detrimental. Therefore, the corresponding demodulation scheme must take into account the non-negligible time-varying frequency offset within the sequence. One possible approach is Post Detection Integration (PDI), in which coherent integration is performed within each segment of a sequence, and non-coherent integration is used to combine the partial results from different segments [13].

D. Reducing Receiver Energy Consumption

In some RCC applications, such as battery-operated clocks and watches, the energy consumption of the RCC receivers might represent a great part of the energy consumed by the entire device. By properly utilizing different reception operations, energy consumption may be minimized:

- The acquisition operation should be performed only once throughout a battery lifetime, unless the maximal time drift t_m becomes greater than ± 30 s, which may occur only if the device has not performed successful tracking operations in a long period.
- The DST transition notification field may change as frequently as twice a year, and leap seconds are usually scheduled only in June and December. Therefore, by combining the efforts of receiving these two fields into one reception, the frequency of the notification reception operation may be reduced

to only twice a year: in June, at which time the schedule for the end of the DST period may be received, and in December, at which time the beginning of the next DST period may be received. In both instances, a leap-second notification for that month may be received.

- The tracking operation can be performed daily or once every few days, while considering the tradeoff between the frequency of tracking and the maximal time drift, which corresponds to the maximum possible time drift experienced in the RCC since the last tracking operation.

  Since a particular crystal would be characterized by a relatively stable error over a fixed period of time, a cognitive receiver, after estimating the error based on WWVB reception, could adjust the time drift without receiving WWVB as frequently, and the resulting t_m can be narrowed. In such case the amount of residual time drift would mainly depend on the temperature stability in which the device is placed.

  Tracking should be performed during nighttime, preferably at 0700 or 0800 UTC (Coordinated Universal Time), for four reasons: (1) The signal strength is stronger during nighttime in locations that are distant from the station; (2) Human activity is at a much lower level at night, leading to lower levels of interference; (3) All the AM bits are ‘0’ (longer duration of high power), resulting in higher overall signal energy; (4) The transmission of Long frames and Medium frames avoids whole hours.

IV. SUMMARY

The new enhanced WWVB broadcast, based on BPSK, offers much improved performance for RCCs when compared to the legacy broadcast, allowing receivers to recover time and timing information reliably from signals that are orders of magnitude weaker, or to operate in the presence of interference that may be orders of magnitude stronger than what can be tolerated by the legacy receivers. The performance superiority of the new broadcast has been demonstrated in multiple locations throughout North America with EverSet® receivers that were designed to receive it [9]. The new broadcast format is backward compatible, such that legacy envelope-detection based receivers are not impacted by its introduction. Various transmission modes are supported, having different bit rates and code rates, to accommodate a wide range of SNRs. In order to reduce receiver energy consumption and enhance reliability, the new broadcast format also enables different receiver operations, such as tracking, allowing a receiver to perform timing adjustments based on a robust and energy-efficient data-aided synchronization operation. Data representation was made more efficient and reliable in the new format by employing compact data encoding and error control coding. The new broadcast format allows new RCCs to deliver higher reliability and accuracy, and enables many new applications to be based on the WWVB broadcast. Several consumer market products are underway based on EverSet® receivers, and it is anticipated that the use of this enhanced broadcast will greatly exceed that of its predecessor.

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REFERENCES

[1] J. Lowe, "Enhanced WWVB Broadcast Format," 2012. Available at: http://www.nist.gov/pml/div688/grp40/wwvb.cfm

[2] P. Hansen and D. Gish, "WWVB Baseline Measurements: Summary, Findings, and Recommendations," U.S. Navy, Tech. Rep. February, 1995.

[3] J. Lowe, M. Deutch, G. Nelson, D. Sutton, W. Yates, P. Hansen, O. Eliezer, T. Jung, S. Morrison, Y. Liang, D. Rajan, S. Balasubramanian, A. Ramasami, and W. Khalil, "New Improved System for WWVB Broadcast," in *Proceedings of Annual PTTI Meeting*, 2011.

[4] J. Burrus, "New NIST Time Code to Boost Reception for Radio-Controlled Clocks," *NIST Tech Beat*, 2013. Available: http://www.nist.gov/pml/div688/wwvb-030513.cfm

[5] Physikalisch-Technische Bundesanstalt (PTB) Braunschweig, "Time and Standard Frequency Station DCF77 (Germany)." 1984. Available: http://www.eecis.udel.edu/~mills/ntp/dcf77.html

[6] Japan Standard Time Group, "The Method of Emitting Standard Time and Frequency Signal Emission." Available: http://jjy.nict.go.jp/jjy/trans/index-e.html

[7] NPL Time & Frequency Services, "MSF 60 kHz Time and Date Code," 2007. Available: http://www.npl.co.uk/upload/pdf/MSF_Time_Date_Code.pdf

[8] M. A. Lombardi, "NIST Time and Frequency Services," *NIST Special Publication 432*, 2002. Available at: http://www.nist.gov/pml/div688/grp40/wwvb.cfm

[9] Y. Liang, D. Rajan, O. Eliezer, S. Balasubramanian, and W. Khalil, "A New Broadcast Format and Receiver Architecture for Radio Controlled Clocks," in *Proceedings of IEEE MWSCAS*, Columbus, OH, 2013.

[10] M. Kuhn, "Efforts to abolish leap seconds.". Available: http://www.cl.cam.ac.uk/~mgk25/time/leap/

[11] Y. Liang, O. Eliezer, and D. Rajan, "Receiver Design of Radio-Controlled Clocks Based On The New WWVB Broadcast Format," *IEEE Trans. Wireless Commun.,* Submitted.

[12] H. Zhou, C. Nicholls, T. Kunz, and H. Kchwartz, “Frequency accuracy and stability dependencies of crystal oscillators,” Carleton University, Systems and Computer Engineering, Technical Report SCE-08-12, November, 2008.

[13] G. Corazza and R. Pedone, “Generalized and average likelihood ratio testing for post detection integration,” *IEEE Trans. Commun.*, vol. 55, no. 11, pp. 2159–2171, 2007.