A New Broadcast Format and Receiver Architecture for Radio Controlled Clocks

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***Abstract*—A new broadcast format is presented for the atomic-clock time-code signal broadcast by the National Institute of Standards of Technology (NIST) from station WWVB in Fort Collins, Colorado. The new broadcast format, based on BPSK modulation that is added to the existing amplitude-modulation (AM), offers many new features and provides several orders of magnitude of improvement in reception robustness, without impacting existing AM receivers that are based on envelope-detection. Additionally, a digital receiver architecture, amenable to integration in a CMOS system-on-chip (SoC), is proposed, which relies on digital signal processing, thereby eliminating the need for the crystal filter and other passive components found in existing receivers.**

I. INTRODUCTION

A digitally represented time-code was first introduced on the WWVB broadcast in 1965. The modulation scheme defined for this broadcast format targeted low-complexity envelope detection receivers, much like what has been used in the reception of AM broadcasts at the time. Additionally, a simple scheme was chosen for the encoding of the information, based on binary-coded-decimal (BCD) representation of the digits, to simplify the decoding and displaying of the received time and date information, when considering the electronics of that era [1] [2]. Consequently, the broadcast was inefficient, when evaluated as part of a digital communications system, resulting in a requirement for a relatively high signal-to-noise-ratio (SNR) for reliable reception. A significant increase in the station's effective radiated power to 70kWatt, which was introduced in 1999, has resulted in the wider adoption of radio-controlled-clock (RCC) products, such as wall clocks and wrist-watches. However, their unreliable operation, particularly indoors, has been impeding the employment of RCCs in various applications such as digital cameras and microwave ovens [3]. Hence, a new system has been proposed, which was deployed in 2012, demonstrating several orders of magnitude of improvement in reception reliability. The proposed receiver architecture for the new broadcast is extensively digital and leverages the capabilities of present day technology, allowing for signal processing of relatively high complexity to be realized in a low-cost integrated circuit (IC).

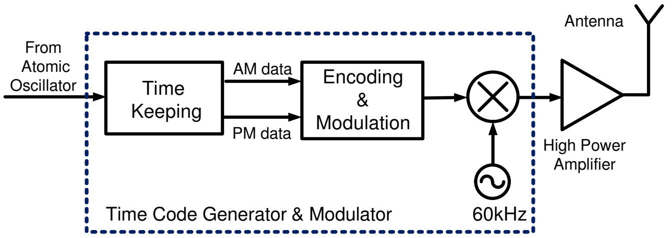


Fig. 1. Simplified block diagram of enhanced WWVB transmitter

Section II describes the new broadcast format and provides analysis for the significant performance gains it introduces. Section III defines the different modes of operation for the proposed receiver and demonstrates the additional enhancement in performance and energy reduction that is achievable in the receiver when it is in tracking mode. Section IV presents the receiver architecture, its simulated performance, and experimental results obtained with a software-based prototype receiver.

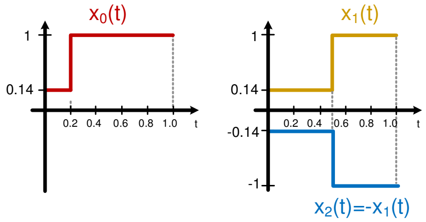
II. THE NEW BROADCAST FORMAT

Figure 1 shows the block diagram for the modified WWVB transmitter, where a time-keeping function produces two separate data streams, corresponding to the legacy and new broadcast formats. The newly added phase modulation (PM) path in the figure exploits the performance gain made possible by efficient digital modulation and coding. Various information rates are supported in the new broadcast, allowing receivers operating at extremely low SNR conditions to trade-off energy consumption with reception reliability. Additionally, RCC devices may employ different reception strategies when first acquiring the time and date versus when periodically compensating for subsequent drift in their timing (*i.e.* tracking). The different reception strategies allow for reliable operation at even lower SNR conditions, while also conserving energy.

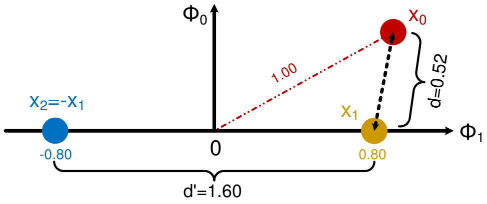
A. The Modulation Scheme

The Modulation scheme chosen for the enhanced broadcast is phase-reversal-keying (PRK), which is antipodal binary-phase-shift-keying (BPSK), wherein the '0' and '1' binary information symbols are represented by two opposite phases of the modulated carrier. The 180° phase reversals that are

This work was partially supported by NIST grant SB134110SE0700.



(a) Baseband waveforms of transmitted signals



(b) Signal space representation of transmitted waveforms

Fig. 2. Comparison of waveforms and Euclidean distances of legacy and new signals

applied to the carrier when a ‘1’ is being transmitted do not affect the operation of envelope-detector based receivers that recover the legacy information from the legacy modulation, thereby maintaining backward compatibility [4].

Figure 2(a) shows the baseband waveforms of both broadcast formats. In the legacy broadcast, the binary symbols ‘0’ and ‘1’ are represented by different pulse durations in a modulation scheme comprising Pulse-Width Modulation (PWM) and Amplitude Modulation (AM), having the baseband waveforms shown by x_0 and x_1. In the enhanced broadcast using BPSK, the binary symbols ‘0’ and ‘1’ are represented by opposite phases. The baseband representation of the addition of the BPSK modulation is shown by x_1 and $x_2 = -x_1$. While this figure, as well as the modulation-gain analysis that follows, imply that the same symbols are sent through the newly added phase-modulation (PM) path, it is to be noted that different data frames are sent through the legacy and new PM paths, resulting in multiple possible combinations of pulse duration and phase reversal [5].

The choice of an antipodal modulation scheme ensures minimization of the bit-error-probability (BER) in the received signal in the presence of additive white Gaussian noise (AWGN). The signal space representation of the legacy and PM waveforms are shown in Figure 2(b). By moving the constellation point of x_1 to its opposite phase $x_2 = -x_1$, the Euclidean distance for the new modulation increases from 0.52 to 1.60. The increase in the Euclidean distance corresponds to a performance improvement of

$$\eta = 20 \times \log(\frac{1.60}{0.52}) = 9.8\text{dB} \tag{1}$$

when assuming that both the legacy and the improved signals are received using matched-filter based optimal receivers. While the proposed receiver for the BPSK signal is demonstrated to have near-optimal performance, the typical receivers in legacy consumer-market RCC products are based on envelope detectors, resulting in an even larger performance gap (well above 10dB) between the two systems.

B. Multiple Transmission Modes

While the legacy broadcast only supports one mode of operation, at a data rate of 1 bit/sec, the new standard can support multiple transmission modes, and thus can support reception under a wide range of SNR conditions. The data content and the start of frame (SOF) timing in each transmission mode include enough information for a RCC that observes Daylight Saving Time (DST) to display the current hour, minute and second. The Normal Mode also includes the year, date, and advance notifications for DST transitions and for leap seconds. A brief description for each of the currently supported modes is provided below.

- The Normal Mode has a bit rate of 1 bit/sec and frame duration of 1 minute, which are the same as in the legacy broadcast. The CNR requirement for robust reception in this mode is about 12dB in a bandwidth of 1Hz. Most RCC devices can experience such CNR or higher during the night throughout the continental US, assuming the shielding losses for indoor reception, as well as the level of interference are limited. The next section focuses on the reception in Normal Mode.
- The Medium Mode has a chip rate of 1 bit/sec and frame duration of 6 minutes. The actual information rate is about 7/254 bit/sec, since two 127-bit sequences are used to represent the 7-bit information representing the minute, hour and DST status. A symbol in this mode, represented by a 6-minute frame, is transmitted every half hour, and therefore RCC devices operating in this mode may need to receive for over half an hour to capture an entire Medium Mode frame. The CNR requirement for this mode, on the other hand, can be as low as -3dB in a bandwidth of 1 Hz.

Future modes that may be supported include an Extended Mode (based on frames/symbols of greater duration than the Medium Mode), and a Fast Mode of higher data rate. The Fast Mode will allow receivers to acquire and to track within shorter periods of time, while requiring a higher SNR for comparable reception reliability. This will offer the advantages of reduced energy consumption, as well as faster response time when first acquiring. The Extended Mode will allow receivers to acquire and to track at particularly low SNR conditions, while consuming a greater amount of energy in each operation, due to the extended duration of the receiver’s operations.

C. The Frame Structure and Data Encoding

This subsection presents the new frame structure and data encoding scheme in Normal Mode and their benefits.

Figure 3 shows the frame structure in both the legacy and new broadcast formats. In the legacy frame structure, M denotes the markers, which are of 0.2 sec duration, and R denotes reserved bits, which have been assigned to ‘0’, having a deterministic pulse duration of 0.8 sec.

The new broadcast includes a 13-bit synchronization word for robust timing recovery. Instead of having separate fields for

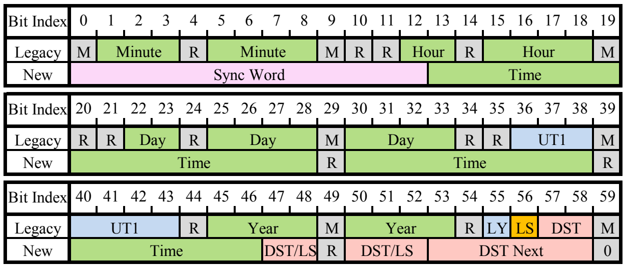


Fig. 3. New frame structure (for Normal Mode) shown against legacy frame

minute, hour, day and year, as in the legacy frame, the new broadcast merges all these fields into one compact 26-bit word representing the current minute in this century. This time word is encoded by a Hamming(31,26) linear block code, resulting in a codeword of 31 bits. The error control coding significantly improves the robustness of the data recovery, especially in the case of impulsive noise. The DST and leap second statuses are indicated by the DST/LS field, which also includes redundant bits to increase the data-recovery reliability. The DST Next field informs RCC devices of the next DST transition schedule months ahead of time, therefore eliminating the need for daily reception of the DST status, which is customary in legacy receivers. The DST Next field is encoded by a non-linear (6,5) block code, which ensures that the most probable DST transition schedule is represented by the codeword of greatest minimum distance.

III. RECEPTION OPERATIONS

The proposed receiver may perform one of 3 operations: 1) acquisition – initial reception of time information, including year, month, day, hour, minute, and daylight saving time (DST) and leap second (LS) status and notification; 2) tracking – frame and symbol timing synchronization for periodic drift compensation; and 3) notification reception – extraction of specific information from the frame, while having at least approximate knowledge of the correct timing (i.e. the start of frame SOF).

Since frame and symbol timing must be recovered before the information bits can be decoded, the frame/symbol timing recovery performed in the tracking operation is also performed in the other two operations.

TABLE I

COMPARISON OF DIFFERENT RECEIVER OPERATIONS IN NORMAL MODE

RX Operation	Frequency of Operation	Reception Duration
Acquisition	once (not needed periodically)	1-2 min
Tracking	once in a few days	13 sec + $2t_w$
Notification Reception	twice a year	1 min + $2t_w$

While acquisition is typically the only operation performed in RCC devices based on the legacy format, the employment of different reception operations in the proposed system brings in significant benefits in reception reliability and in energy conservation. As shown in Table I, the tracking operation, which is done most frequently, requires a much shorter reception duration than that of the acquisition operation.

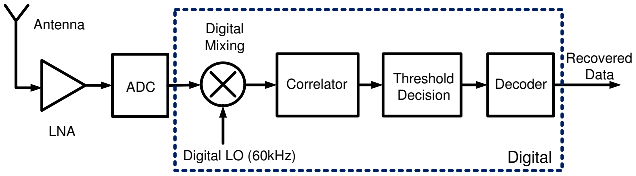


Fig. 4. Simplified block diagram of receiver for new BPSK broadcast

IV. RECEIVER STRUCTURE AND MEASURED RESULTS

As shown in Fig. 4, the proposed receiver relies on digital processing for the demodulation and decoding of the information represented in the phase of the received signal. This section presents some of the principles of operation of the receiver, as well as simulation results and field test results for the proposed receiver.

A. Receiver Principles of Operation

If the receiver's operations are based on a crystal oscillator of 20ppm accuracy, from which the digital LO signal would be derived, a maximum frequency error of 1.2 Hz, with respect to the 60kHz carrier of the received signal, may be experienced in the receiver. The corresponding normalized frequency offset with respect to the symbol rate is $\Delta f_0/R = 1.2$, where symbol rate $R = 1$ bit/sec. At the RCC receiver, symbol timing recovery and frame synchronization are performed in the presence of such unknown and large frequency offset under challenging SNRs. Therefore, it is desirable to perform a one-shot joint symbol and frame synchronization operation, which also accounts for the large frequency offset, such that the decision is made by exploiting the entire known sync word. It is for this reason that a relatively long duration is allocated to the sync word, carrying no time information, with respect to the data frame duration of 60 seconds in Normal Mode.

Prior work on frame synchronization in the presence of frequency offset assumes the frequency offset is a fraction of the symbol rate [6]–[9]. While this assumption holds true in many practical communication systems, it is invalid for the proposed receiver. Hence, a joint symbol and frame synchronization scheme is used, which considers the presence of very large frequency offsets and is applicable to RCC devices. Simulated performance of receiving Normal Mode time frames is shown, with both acquisition and tracking operations, but the detailed description of the algorithm is not covered here.

B. Simulation Results

Simulations were performed to evaluate the synchronization performance of the proposed receiver. The performance metric is the probability of false synchronization (PFS), which is defined as the probability that the difference between the estimated timing, obtained through the synchronization operation, and the correct timing, defined by the broadcast signal, is greater than half a symbol duration (i.e. 0.5 sec in Normal Mode). In the simulations, an oversampling rate of $N = 4$, a timing ambiguity window of up to $t_w = 6$ seconds on each side, and a frequency offset uniformly distributed from -2Hz to 2Hz are assumed.

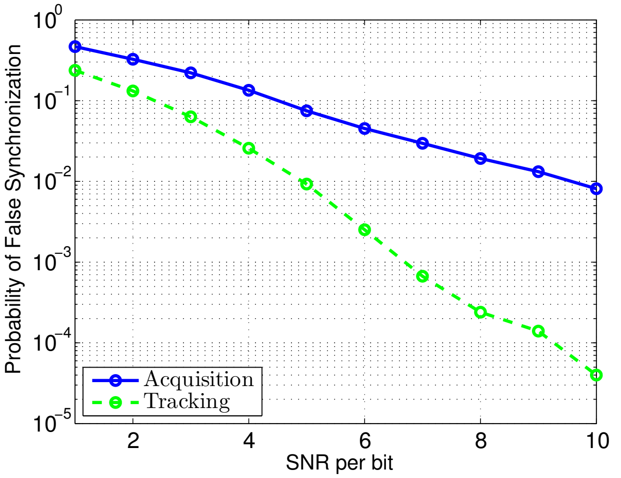


Fig. 5. Probability for false synchronization in Normal Mode reception

Figure 5 shows the PFS for acquisition and tracking operations. Under the same SNR conditions, the PFS for the tracking operation is shown to be much lower than that of acquisition. This is because the SOF search for tracking is performed within a much smaller time window compared with that of acquisition. The probability of a frame synchronization error for acquisition operations can be further reduced by exploiting the channel coding to detect scenarios of false (i.e. invalid) synchronization. When considering the coding schemes used in the Time, DST/LS and DST Next fields, the probability that no error is detected, while the synchronization is invalid (i.e. random/incorrect data), is about 10^{-3}. Therefore, the use of error detection in the various coded data fields can serve as a reliability assurance measure for acquisition. When combining the probability of an undetected error in random data with the probability of independent false synchronization event PFS= 10^{-2} at SNR of 10dB, the proposed receiver can achieve a probability of a frame error of 10^{-5} in acquisition. For the same SNR of 10dB, as shown by Figure 5, PFS= 4×10^{-5} for tracking operations. It should be noted that the consequences of invalid acquisition (i.e. wrong time/date assumed) are far worse than those of a failure in tracking (i.e. timing error of a few seconds). Assuming 10^{-5} as the maximal allowed probability for a frame error in acquisition and for a synchronization error in tracking, the SNR threshold for reliable operation in the proposed receiver is 10dB, which maps to a slightly higher CNR value when considering the AM that is present on the signal. Hence, when compared with the typical required CNR of 30dB (in 1Hz bandwidth) that is found in existing RCC products based on envelope detection, the proposed receiver operating in Normal Mode offers a performance improvement of 18dB.

C. Reception Trials

Empirical validation of the performance of the system confirmed that reliable reception (no invalid frames observed) can be obtained at a CNR of 12dB, in agreement with the simulated results. This performance validation was obtained in a lab setup, where a controlled amount of attenuation was placed between a prototype receiver and a time-code-generator (TCG) emulating the enhanced WWVB broadcast.

Furthermore, field reception trials with a prototype receiver were performed against the actual broadcast from Fort Collins, Colorado, demonstrating noticeable superiority when compared to existing legacy products. Reception locations included Dallas, Orlando, New York, Boston, Columbus (Ohio), Quebec City (Canada), San Diego, San Francisco, Alaska, and Hawaii. In particular, significant performance superiority was noticeable in large buildings, where high shielding losses are experienced, and/or in proximity to interfering devices, where legacy devices typically failed to receive even overnight, while the prototype BPSK receiver demonstrated robust reception.

V. CONCLUSION

A new broadcasting system and corresponding digital receiver architecture were presented, which were successfully deployed to achieve 2-3 orders of magnitude of improvement in the reliability of the reception of the WWVB time-code signal in North America. The newly added BPSK modulation was shown to result in 10dB in receiver performance enhancement, while additional features of the new broadcast provide additional significant performance benefits. The extensively digital architecture of the receiver allows for its realization in a CMOS IC, leading to a scalable low-cost and low power integrated solution that may be incorporated into many different products.

ACKNOWLEDGMENT

The development and deployment of the new WWVB broadcasting system, as well as its ongoing maintenance, are made possible by the dedicated work of NIST employees from the Time and Frequency Division, and in particular Matthew Deutch, Glenn Nelson, William Yates, Douglas Sutton, and John Lowe. The development, assembly and testing of the new time-code-generators and prototype receivers were carried out by the team at Xtendwave in Dallas, Texas.

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