Interference-Robustness Improvement in BPSK Receivers for the Enhanced WWVB Broadcast

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***Abstract* — Radio controlled clocks (RCCs) based on the WWVB broadcast, commonly referred to as "atomic clocks", might experience relatively high levels of on-frequency interference from the equivalent MSF time-code broadcast from the UK, particularly on the East Coast. The problem may be further exacerbated by a random orientation of the RCC device, which might favor the reception of the interfering signal. While the legacy receivers for WWVB, based on envelope detection, are particularly vulnerable to such interference, a basic coherent BPSK receiver for the enhanced broadcast demonstrates a 25 dB performance advantage in interference immunity. An interference cancelation technique is proposed, to further enhance the performance of the coherent BPSK receiver, achieving an additional 14 dB improvement in interference rejection.**

***Index Terms* — radio controlled clock (RCC), atomic clock, WWVB broadcast, MSF broadcast, on-frequency interference.**

I. Introduction

Radio controlled clock (RCC) products (e.g., wall-clocks, wristwatches, bedside alarm clocks) have become increasingly prevalent in the US, following the increase in the WWVB station's broadcasting power to 70 kW, as well as the introduction of many low-cost consumer-market products that were designed to receive it [1]. However, its modulation scheme and encoding of information, defined in the 1960s, impede reliable reception at low signal-to-noise ratio (SNR) conditions or in the presence of interference. In particular, in locations distant from the station in Colorado, such as on the East Coast, reception has often been unreliable even during the nighttime, when propagation conditions are favorable [2]. To address this, the National Institute of Standards and Technology (NIST) introduced an enhanced broadcast in 2012, which included the addition of phase-modulation (PM) on the same 60 kHz carrier that continues to carry the legacy modulation and data, allowing for backward-compatibility with the legacy RCC products. This new modulation scheme is antipodal binary phase-shift keying (BPSK), for which the distance between the "0" and "1" in the signal space is maximized. Additional features in the new broadcast further enhance its robustness and effective coverage [3]-[5].

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In particular, the immunity to on-frequency interference has been greatly improved, thereby effectively addressing the interference from the equivalent British broadcast MSF, operated by the National Physical Laboratory (NPL) from Anthorn, UK, having the same carrier frequency 60 kHz [6]. Although MSF is across the Atlantic Ocean and its transmission power is lower, the relative level of its signal received on the East Coast may be intolerably high. Since the legacy receivers are typically based on envelope detection of the amplitude-modulated legacy broadcast [7], they are particularly vulnerable to such interference, whereas the interference immunity of BPSK receivers for the enhanced broadcast is inherently superior, and it is further improved by the technique proposed here.

II. Characterization of the Interference from the MSF Broadcast

Figure 1 shows the simulated signal-to-interference-plus-noise ratio (SINR) values, in terms of relative field intensities, for three different locations on the East Coast over the course of a day, when assuming that the receiver's antenna is omnidirectional, thereby presenting the same gain for the interfering MSF signal and the WWVB signal. However, in a typical RCC, a ferrite-rod antenna is used, having a directional radiation pattern similar to that of a loop. Hence, the actual SINR experienced in the receiver can deviate from the values shown in Fig. 1, depending on the orientation at which the RCC device is placed.

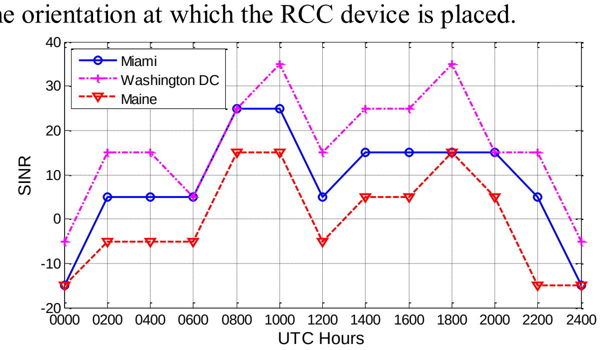

Fig. 1. Simulated SINR during the course of 24 hours in Miami, Washington DC, and Maine (provided by SPAWAR, US Navy)

The SIR, or *S/I*, when considering the antenna orientation, is given by:

$$S/I = \frac{\cos^2 x\, P_s}{\cos^2 y\, P_I} = \left(\frac{\cos x}{\cos(x-z)}\right)^2 S'/I'$$

where *S'/I'* is the SIR in terms of field intensity shown in Fig. 1, and x and y represent the receiver's orientations towards WWVB and MSF, respectively. For example, x equals zero if the receiver antenna points perfectly towards the WWVB station. Angle $z=x-y$ depends on the relative locations of WWVB and MSF with respect to the receiver, and equals the difference of initial bearings from the receiver to WWVB and to MSF, where the initial bearing can be calculated using Vincenty's formulae [8].

The SIR correction factor (in dB) associated with the antenna orientation is defined as:

$$\eta = 20\cdot\log_{10}[\cos x/\cos(x-z)].$$

Its cumulative distribution function (CDF) for receivers in Miami, Florida, is shown in Fig. 2. This CDF reveals that more than 10% of the receivers will experience a loss in SIR that is worse than 15 dB due to the random orientation of their antenna. Such loss is to be applied to the SIR values anticipated by the simulation results of Fig. 1 across the entire 24 hour range (assuming a stationary receiver), potentially reducing even the highest SINR values (e.g., 25 dB for Miami at 1000UTC) to intolerably low values. It should be noted that the nighttime SNR may be very high, allowing the interference from MSF to dominate the receiver's performance.

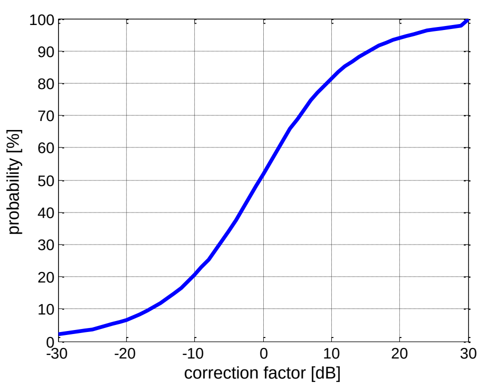

Fig. 2. The CDF of the correction factor η

III. Vulnerability of the Legacy WWVB Receivers to Interference from MSF

In a typical envelope-detection based receiver used in legacy RCC commercial products, analog circuitry determines the signal's high and low amplitudes, V_H and V_L, and the threshold $V_{thr}=0.5(V_H+V_L)$, based on which the duration of the low and high amplitudes in each symbol are determined (for bit decisions) [9]. The envelope detection based demodulation and information recovery is illustrated in [2], where the impact of the on-frequency interference from MSF is shown to be potentially detrimental.

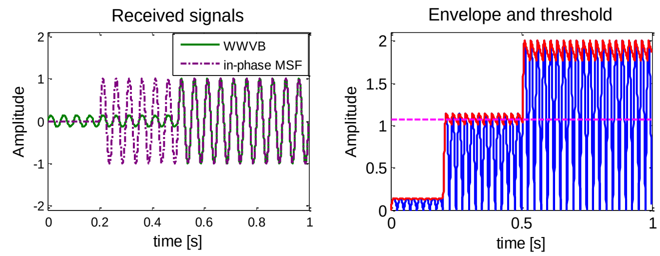

Fig. 3. An example of a corrupted bit decision due to additive MSF interference

In the presence of on-frequency interference, the non-linear envelope detection operation produces baseband levels that do not correspond to those of the WWVB signal, potentially resulting in errors, as shown in Fig. 3, where the bit decision is corrupted by an in-phase MSF signal (with bit A "1" and bit B "0") of equal amplitude. In this example, the additive interference from MSF throughout the one-second duration of the WWVB symbol increases the amplitude of the received signal from t=0.2s to t=0.5s, causing the threshold to be crossed prematurely and thus resulting in an erroneous bit decision of "0" instead of "1".

IV. Improved Robustness to Interference from MSF in the New WWVB Receivers

While the performance of the conventional envelope detection based receiver is highly sensitive to interference from MSF, the optimal coherent BPSK reception of the new broadcast exhibits significantly improved robustness to it. The bit decision operation in such receiver can be illustrated by a BPSK constellation diagram in the signal space, in which the MSF interference can be represented by a vector having an amplitude and phase that are determined by the SIR and phase relationship between the carriers of the MSF and WWVB signals. The addition of the MSF signal to the WWVB "0" and "1" symbols is equivalent to shifting the two signal points in the constellation from their initial center at the origin, to a new center that is dictated by the interference, while keeping the same Euclidean distance between them [2]. Hence, by assessing the level of interference, the signal constellation can be effectively moved back to the origin, thereby eliminating the impact on bit decisions. However, in the presence of timing uncertainties and noise, the interference may be estimated inaccurately, resulting in some residual impact.

A. Signal Model

In RCC receivers based on the enhanced WWVB broadcast, both symbol and frame synchronization are jointly estimated, based on the sync word, by oversampling the received signal [10]. The oversampling rate is denoted by *N*. The sync word length, frame length (in samples) for the WWVB signal are denoted, respectively, by N_s and N_f. The receiver's local-oscillator (LO) is assumed to be perfectly synchronized with the carrier of the received WWVB signal. The k^{th} sample, r_k, of the real baseband received signal, $\boldsymbol{r} = (r_0, r_1, \dots, r_{N_{rx}-1})$, is given by:

$$r_k = \begin{cases} c_{k-m} + AI_k + n_k & if\ k \in \varphi_m \\ d_k + AI_k + n_k & if\ k \notin \varphi_m \end{cases}$$

where $\boldsymbol{c} = (c_0, c_1, \dots, c_{N_s})$ are the transmitted sync word samples, $\boldsymbol{d} = \{d_k, \forall k \notin \varphi_m\}$ are the transmitted random data samples, and $\boldsymbol{I} = (I_0, I_1, \dots, I_{N_{rx}-1})$ are the samples of the interference from MSF. Set $\varphi_m = \{m, m+1, \dots, m + N_s - 1\}$ denotes the indices of sync word samples given that the SOF is at time instance *m*. Both the WWVB and MSF signals are pulse-width modulated with synchronized symbol timing (aligned with the second boundary), as specified in [3] and in [6], and their samples are normalized to have an amplitude of one (when at full power). *A* is the real scaling factor for the interference, determined by the SIR and the phase offset of the interfering MSF signal with respect to the received WWVB signal. Noise samples n_k are Gaussian with variance $\sigma^2 = N_0/E_s$, where N_0 is the noise power spectral density and E_s is the energy per sample period when the transmitted waveform is at its full-power intervals. Note that E_s is 1/*N* of the bit energy.

B. *Algorithm for Cancellation of Interference from MSF*

The goal of the algorithm is to estimate the level of the on-frequency interference, *A*, and remove it from the received signal. Since the estimation of the interfering signal from MSF depends on the symbol timing, the synchronization (frame and symbol) and interference cancellation operations are performed jointly, as outlined in Fig. 4. While the WWVB signal is both PM and AM modulated, the MSF signal is only AM modulated. Therefore, the estimate of the relative amplitude of the MSF signal, $\hat{A}$, is based on the mean of the samples in set λ_i, which are all in the interval 0.5 to 1 s of the one-second symbol. These samples coincide with the full-power intervals of both the WWVB and MSF time-synchronized AM/PWM signals [3], [6]. The estimated MSF interference level, however, is unbiased only if the number of "0" and "1" in WWVB's PM information are equal, which is not necessarily true for all realizations. To remove the potential bias, $\hat{A}(i)$ can be refined after the bit decisions for unknown bits are made for every timing *i*. The cardinality of set *X* is denoted by *C(X)*. The cancellation of the MSF interfering signal is implemented on sample set η_i, the set of indices of samples in the interval 0.5 - 1 s of the MSF markers and 0.2 - 1 s of the MSF information symbols, given that *i* is the SOF. Set η_i includes the samples that are affected by MSF. Since the MSF carrier may be either on or off in the interval 0.1 - 0.2 s, depending on the transmitted information symbol [6], the cancelation does not take place during that interval, and thus both the sync word waveform $\boldsymbol{c}$ and data envelope $|\boldsymbol{d}|$ in the subsequent calculation of the ML criterion should mask out that duration.

After the interference is cancelled, the ML criterion in [10] is used for synchronization, where $|d_l|$ is the l^{th} sample of the random data symbol envelope. The estimated timing, $\hat{m}$, is the one that maximize the ML criterion. The set of indices of sync word symbols, given that *i* is the SOF, is denoted by φ_i. The set of sample indices that belongs to the j^{th} symbol is denoted by γ_j.

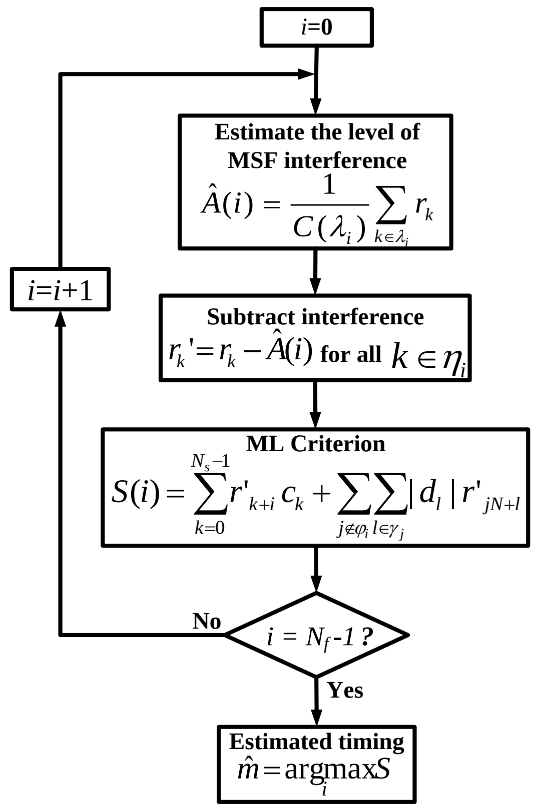

Fig. 4. Flow chart of proposed joint MSF cancellation and synchronization scheme

V. SIMULATION RESULTS

The performance of a coherent PM receiver was compared to that of an envelope-detection based AM receiver in the presence of dominating interference from MSF (i.e., high S/N and low S/I ratios). In order to limit the comparison to the modulation/detection schemes, only raw bit/frame errors were considered (i.e. without considering the channel coding). For both the AM and PM receivers, four relative phase offsets ϕ of MSF with respect to WWVB were simulated: 0, $\pi/6$, $\pi/3$ and $\pi/2$. Since the WWVB signal is also modulated in phase, each BPSK symbol may either maintain the carrier phase or shift it by 180° (i.e. carrier inversion). Hence, the relative phase offsets are both ϕ and $\phi + \pi$.

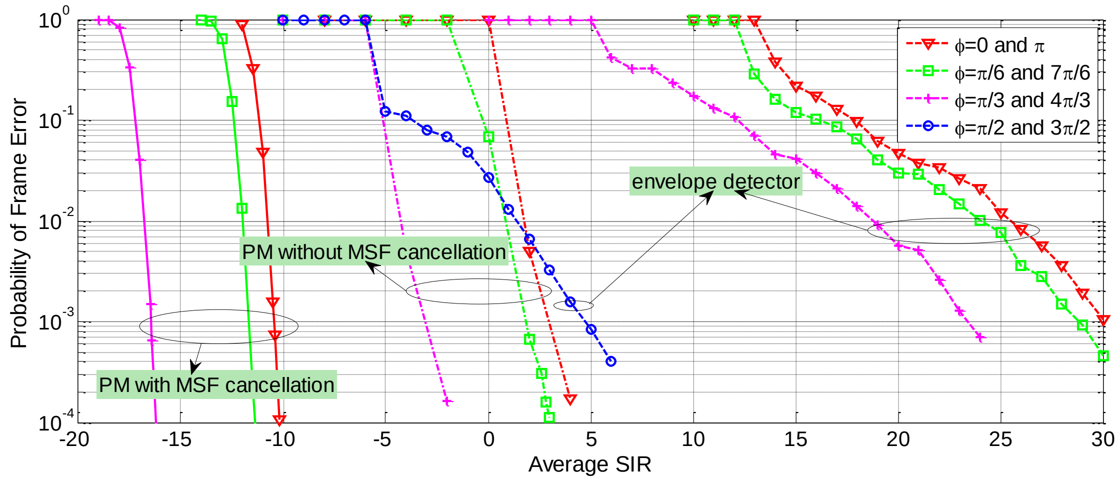

Fig. 5. Frame error rate (FER) at SNR = 40 dB in the presence of MSF interference at various relative phases

The effect of interference from MSF is studied here for the case where reception performance is dominated by it rather than by noise. Hence, Fig. 5 shows the frame error rate (FER) at a relatively high SNR of 40 dB, where the FER is the probability that at least one bit error occurred in a frame. Under such conditions, the FERs of both receivers are nearly zero in the absence of MSF interference, and hence are not seen in the logarithmic y-axis of Fig. 5.

The coherent BPSK demodulation is inherently 25 dB more robust against on-frequency interference (such as the MSF signal) when compared to non-coherent envelope detection. The proposed cancellation technique further improves its robustness by 14 dB for relative phase offsets of 0, $\pi/6$ and $\pi/3$. For the phase offset of $\pm\pi/2$, the MSF interference is orthogonal to WWVB and hence does not impact the reception of the coherent BPSK receiver. By contrast, MSF interference at all phase relationships degrades the performance of the envelope-detector based receiver.

VI. Conclusion

The robustness to on-frequency interference demonstrated by the coherent BPSK receiver designed for the new WWVB broadcast was compared against that of the conventional legacy receivers based on envelope detection. Simulation results for high SNR conditions show that the coherent PM receiver exhibits a 25 dB performance advantage in SIR over the envelope detector, confirming the inherent robustness of the BPSK modulation against on-frequency interference. A joint synchronization and interference cancellation scheme is proposed, which was shown to further improve the robustness of the coherent BPSK receiver by 14 dB, thereby improving its immunity to the on-frequency interference from the MSF broadcast.

Acknowledgement

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