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SIMPLE, EXACT MODELS OF SAMPLE-INTERLEAVING DEMODULATORS/MODULATORS FOR QUADRATURE BANDPASS SAMPLING/RECONSTRUCTION

Dan P. Scholnik and Jeffrey O. Coleman

Department of Electrical Engineering
Michigan Technological University
Houghton, MI 49931-1295
`scholnik@wizard.nrl.navy.mil` `jeffc@mtu.edu`

Abstract— **Bandpass-sampling systems for complex demodulation are now commonplace in the literature, and a few corresponding bandpass-reconstruction systems for modulation have appeared. But their many apparently distinct topologies, filters, and system parameters and the many approaches used in those designs have obscured their common conceptual underpinnings. We present here a simple, unifying approach to the design of such systems, an approach that generalizes the usual two or four parallel processing arms to an arbitrary number of arms and generalizes the usual real digital filters to complex digital filters. Because a straightforward model built around a single, key filter exactly describes any system of this type, custom design of such a system, including optional spectral shaping, reduces to custom digital-filter design.**

Keywords— **quadrature bandpass sampling**

The drawbacks of the analog hardware traditionally used for modulation and demodulation have prompted much research into using increasingly powerful DSP systems as a replacement, especially for demodulation. These systems sample the bandpass-filtered IF signal directly and use digital processing to produce samples of the complex modulation envelope. The theory of bandpass sampling on which the most efficient previous designs are based was explored in [1–3]. The first implementations of bandpass-sampling demodulators appear to be by Waters and Jarrett [4] and Rice and Wu [5], which were published simultaneously in the same journal and describe essentially identical systems. Variations of this approach can be found in [6–12]. A different method (using simple Nyquist sampling) due to Rader [13] was later used and extended in [14–18]. Modulator implementations corresponding to a reversal of Rader's method can be found in [17–19]. In his project report [20] Pohlig touches peripherally on some of the concepts below while focusing on a design for a specific application.

The operation of the Fig. 1 models is described by the Fig. 2 spectra, which depict (top to bottom) the modulation of a complex discrete-time signal, to produce a (real) analog bandpass IF signal, and (bottom to top) the corresponding demodulation. These models invite intuitive analysis and custom design using standard filter-design tools, and they will be shown to be equivalent to the realizable systems of Figs. 3 and 4.

The models are simple. The modulator shifts a "desired" spectral lobe of input spectrum $D(f)$ to f_c and maps sequence values to weighted impulses to drive filter $G(f)$. Tapped-delay-line filter $G(f)$ (complex-weighted taps with spacing T_s/M) and the analog bandpass filter

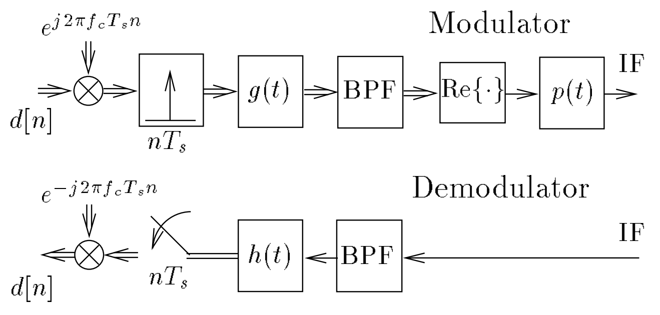

Fig. 1. Analytical models of the modulator and demodulator. Double lines indicate complex quantities.

together pass and shape only that desired lobe, and taking the real part adds the conjugate spectral reflection. Finally, response $P(f)$ represents the D/A hold function. The demodulator is functionally opposite, as $H(f)$ and the BPF isolate and shape just the desired positive frequency lobe of the bandpass signal and the sampler produces spectral copies, one of which is then shifted to DC.

The models are easily transformed into the realizable systems of Fig. 3. Start with the demodulator. The support of TDL impulse response $h(t)$ is contained in $\cup_{i=1}^{M}(\mathbb{Z} - \frac{i}{M})T_s$, so the TDL filter decomposes into a polyphase bank of M TDL filters with $(\mathbb{Z}-\frac{i}{M})T_s$ contain-

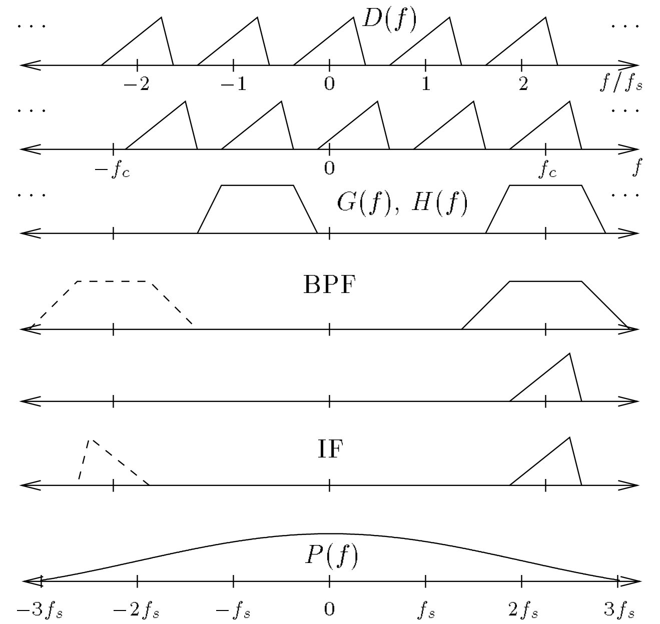

Fig. 2. Example signal spectra and filter responses ($M = 3$).

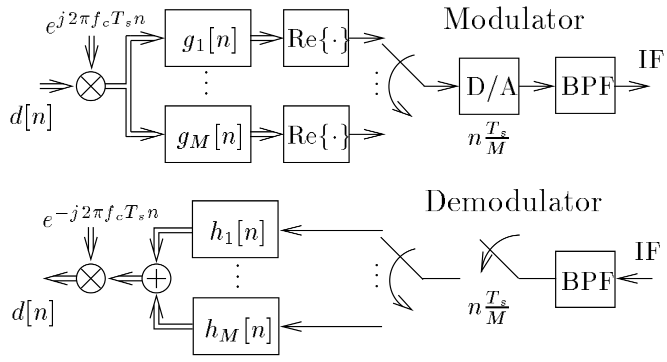

Fig. 3. Realizable modulator and demodulator systems.

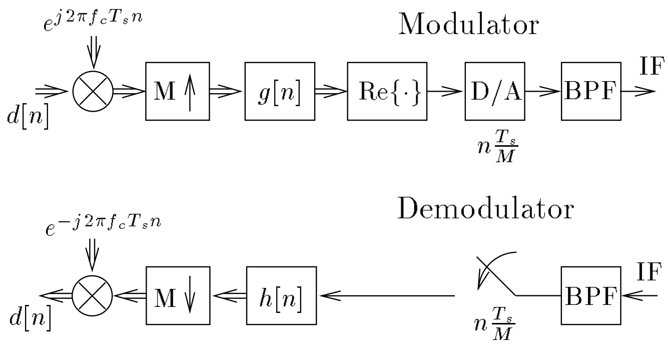

Fig. 4. Alternate implementations.

ing the support of the filter i impulse response. Pushing the sampler through this TDL filter bank transforms TDL filter i into discrete-time filter $h_i[n]$ operating on samples taken at times $(\mathbb{Z} + \frac{i}{M})T_s$. The common input is then a sample stream spaced at T_s/M. In the modulator the impulse mapper is pushed through a similar TDL filter bank to yield discrete-time filters followed by mappers, with mapper i creating impulses at times $(\mathbb{Z}+\frac{i}{M})T_s$. The M mappers combine into a single mapper with impulses spaced at T_s/M. The BPF impulse response is real, so the mapper, BPF, Re{·} operator, and hold response $P(f)$ reorder into Re{·} operator, mapper, response $P(f)$, and BPF. The center two are the D/A.

If the sampling and impulse-mapping steps in Fig. 1 are decomposed instead of the TDL filters, the alternate implementations of Fig. 4 are easily developed. In the demodulator, the sampling step can be decomposed into sampling at the higher rate Mf_s, corresponding to the TDL filter's tap spacing, and a subsequent decimation by M. Pushing the new higher-rate sampler through the TDL filter transforms the latter into discrete-time filter $h[n]$. A DC null in this filter's response, when not in conflict with other system requirements, can be imposed to cancel any A/D offset. Similarly, the modulator's impulse mapping is decomposed into an interpolation by M followed by a mapper operating at rate Mf_s. This higher-rate impulse mapping can now be pushed through the TDL filter to create discrete-time filter $g[n]$. The other blocks are rearranged as before.

Parameter choices limit the customization possibilities offered by TDL filter $G(f)$. The spectral regions to be shaped and suppressed (around $\pm f_c$) must be disjoint modulo Mf_s, the period of $G(f)$, so that the specification of $G(f)$ in those intervals does not conflict. More processing arms increase this period allowing greater flexibility and weaker constraints on both $G(f)$ and IF filtering at the expense of more computation and faster A/D and D/A converters. We present design examples in [21]. Finally, straightforward extension to nonuniformly spaced TDL taps permits further design flexibility.

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