Suboptimal Detection of Telemetry Signals: Functional Simulation and VLSI Implementation

Miljan Vuletić, Goran Davidović, and Veljko Milutinović
Department of Computer Engineering
School of Electrical Engineering
University of Belgrade
POB 35-54, 11120 Belgrade, Serbia, Yugoslavia
email: {miljan@galeb, davidovic@buef31}.etf.bg.ac.yu, vm@etf.bg.ac.yu

Abstract

Utility telemetry service allows utility providers to minimize their expenses and maximize service quality and competitiveness, using public switched telephone networks. The newly emerging IEEE standard 1390 defines alert signals for network to telemetry interface, which activate the telemetry interface unit. Since this standard is on a relatively specific subject, VLSI detectors for the IEEE 1390 signals are not wide-spread on the market. Instead of using optimal detection methods, a detector of these signals is suggested here, based on suboptimal detection methods. The analysis has been performed in several steps: a) mathematical modeling, b) simulation analysis, and c) implementation analysis. The performed analysis indicate that suboptimal methods offer satisfactory performance, even with a relatively large quantization noise, which implies lower VLSI complexity and production cost.

1. Introduction

The IEEE 1390 standard describes the telephone network interface to a Telemetry Interface Unit (TIU) operating under the Utility Telemetry Service Architecture [1]. The TIU is a Customer Premise Equipment (CPE) device that provides network communication interface to one or more meters (water, gas, and electric), or other control devices. Finding a way to successfully detect alert tones (non-power ringing tones) that initiate communication with TIU is the main objective of our analysis.

The CPE Alerting Signal (CAS) is a dual tone alert signal, recommended by Bellcore, that is often used in telemetry (although not defined by the IEEE 1390) and other applications. It is sent by Central Office in order to: a) indicate a call waiting, and b) initiate Caller ID data transfer sequence.

If a VLSI implementation of a detector for signal types defined by the IEEE 1390 is considered, suboptimal detection methods [2] have to be taken into account, as they provide very low implementation complexity. Since suboptimal detectors occupy less VLSI area than optimal ones [3], this is the main reason of their low-cost applicability, which always implies their importance for market-oriented design and development [4].

2. Problem definition

The goal of this work is to design two separate VLSI detector cores for the IEEE 1390 signals and the CAS signal detection. These detectors should be totally independent, but still may coexist on a single chip die, if they are part of more complex design that integrates all functionalities needed for TIU and telemetry architecture.

2.1. The IEEE 1390 signals detection

The IEEE standard 1390 defines two possible ways of alerting the TIU: a) using Single Alert Tones (SAT), or b) using Dual Alert Tones (DAT). The part of every TIU is a signal detector responsible for detection of the IEEE 1390 signals. After any of these signals is detected, the TIU changes its state from inactive to active and connects to the center that requests meter reading. A detection technique for detecting SAT/DAT signals, capable of a low-cost VLSI implementation and further component integration, should be devised.

2.2. The CAS signal detection

Prior to sending CAS signal to the destination CPE, Central Office mutes the remote end speaker. While CAS is being sent, destination CPE is Off-Hook and local speaker is generating speech which buries CAS into a non-white noise. Specific algorithm should be devised, in order to find the applicable solution for low-cost VLSI implementation and further component integration.

3. Existing solutions

Existing solutions often suggest the use of optimal detection methods which offer more than satisfactory performance, but rather high implementation complexity and VLSI cost. Increase in the required VLSI area implies higher fabrication cost of a detector chip.

Since the IEEE standard 1390 is on a relatively specific subject, VLSI detectors for the IEEE 1390 signals are not common at the market. Several solutions to the CAS signal detection problem exist, but few have achieved satisfactory performance in real conditions. Some existing solutions [5, 6] suggest the use of specialized detector chip together with a microcontroller that performs flow control of detection algorithm.

4. Suggested solution

Suboptimal detection methods are the basis of the suggested solution. Since a performance-cost curve has an optimum, one has to make careful decision while lowering implementation complexity, in order to achieve this optimum. The following suboptimal detection methods are taken into account:

- DMF (Digital Matched Filter);
- WPD (Weighted Partial Decision);
- SAS (Sample and Sum);
- BMF (Binary Matched Filter);

When BMF detection method is used, input and local signal are hard limited and coded only with one bit (sign). The methods SAS (or WPD) assume coding of local (or input signal) with only one bit, respectively. If it is used with extremely large quantization noise, the DMF detection method may be considered suboptimal [7].

5. Conditions and assumptions

In the performed analysis, the following conditions are respected and assumptions taken, for both of the above mentioned detection problems (IEEE 1390 signal detection and CAS signal detection).

5.1. IEEE 1390 conditions

- A single TIU may be alerted by one or more single or dual alert tones. The following tones are used for alerting a TIU in inactive state and On-Hook:
  a) Single alerting tones (SAT):
  $\{f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8, f_9\}$, and
  b) Dual alerting tones (DAT):
  $\{f_g$ & f_x, where f_x is $f_1, f_2, f_3, f_4, f_5, f_6, f_7$, or $f_8\}$
  The above mentioned frequencies are [in Hz]: $f_1 = 375.2$, $f_2 = 404.3$, $f_3 = 468.0$, $f_4 = 495.8$, $f_5 = 520.6$, $f_6 = 548.0$, $f_7 = 562.8$, $f_8 = 578.4$, $f_9 = 1633.0$, $f_g = 1827.0$.
- The telephone network sends out an alert tone for 600ms or less (goal), 1000ms maximum duration if subaddressing is present.
- False alerts shall be prevented: a) harmonics, b) voice, c) DTMF (Dual Tone Multi Frequency).
- The allowed frequency shift for all frequencies is ±1%.

5.2. IEEE 1390 assumptions

- Possible amplitude distortion in the case of single alert tone: -3dB.
- Possible relative amplitude ratio in the case of dual alert tone: -6dB.
- Signal to Noise Ratio (SNR): 10dB.
- Impulse noise duration: Impulse noise consists of 5 pulses each one 1% of the signal duration.
- Burst noise duration: Duration of 5% relative to the signal duration.
- Separate detectors for low (f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8) and high (f_9, f_g) frequency sets are supposed.

5.3. CAS conditions

- CPE Alerting Signal (CAS) has been recommended by Bellcore for CPE devices that are in the Off-Hook or active state.
- CAS is a dual tone signal consisting of two frequencies [in Hz]: $f_{CAS} = 2130$ & 2750.
- False alerts shall be prevented.

5.4. CAS assumptions

- CAS signal duration: minimum 75ms; typical 80ms; maximum 85ms.
- Relative signal level ratio of the two CAS components: minimum -7dB; maximum +7dB.
- Maximum allowed frequency shift is ±1% of the nominal frequency values.
- Signal to noise ratio (SNR) is assumed to be -20dB.

6. Mathematical modeling

In order to adapt suboptimal detection methods to the particular problem, mathematical modeling has been performed for both detection problems (IEEE 1390 signal detection and CAS signal detection), conforming to the well-proven VLSI research methodology [8].

6.1. Modeling the IEEE 1390 signal detection

A modified detection technique, compared to the solution given by [9] had to be used for detection of signal types defined by the IEEE 1390 standard, since the alert tone frequencies are close to each other, while maximum allowed frequency shift is relatively large compared to the distance between frequencies. In order to improve the detection performance and not to increase the complexity, three frequency samples per alert tone frequency are taken into account, when determining the presence of the alert tone. The choice of DFT resolution is made based on the following conditions, derived during the analysis:

$$\Delta f \geq \frac{2}{3} \cdot 0.01 \cdot f_{\max} \quad \text{and} \quad \Delta f \leq \frac{f_{i+1} - f_i}{4} \quad ,$$

where Δf is the distance between two DFT frequency samples in the frequency domain; f_{i+1} and f_i are actual neighboring alert tone frequency samples in the frequency domain, and f_{max} is the maximum frequency from the observed set of alert tone frequencies.

The detection problem has been partitioned, and the low and the high frequency sets are formed, that can be treated more appropriately, without introducing additional complexity. The output states of both detectors can be used for determining the presence of a single/dual alert tone.

6.2. Modeling the CAS signal detection

Since the CAS signal is buried in speech generated by the local speaker and the detection time is limited, it is difficult to recognize it accurately. Detection methods, based on the DFT, like that used for the IEEE1390 signal detection are not applicable to this problem. Instead, the correlation function was chosen to distinguish the CAS signal from the noise. If the CAS signal is detected *N* times in the last *M* detections (where $M > N$), it could be the alert tone. Approval of the above assumption and prevention of false alerts is achieved by introducing a mute interval of duration about 10ms.

The CAS detector works in cycles, and transfers from one state to another if an appropriate condition appears (Figure 1). The duration of M detection cycles together with duration of the mute interval is chosen to be shorter than the CAS signal duration.

7. Simulation analysis

An exhaustive simulation analysis has been performed in order to prove the applicability of suboptimal detection methods to IEEE 1390 and CAS signal detection, and to find out the worst conditions of exploitation.

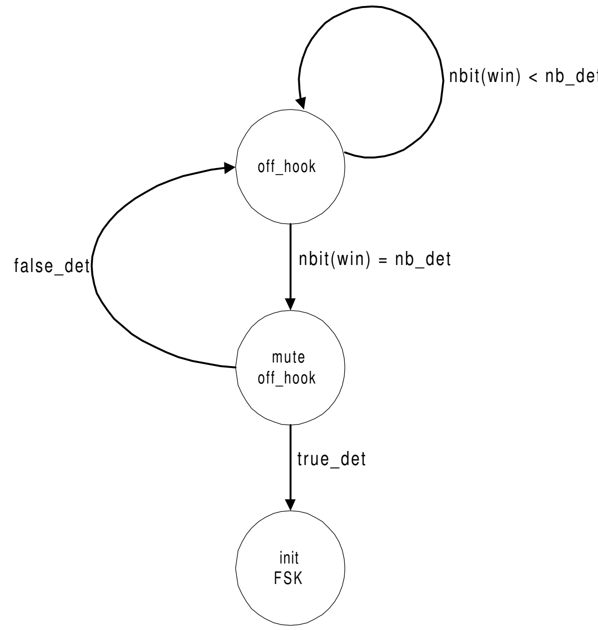

Figure 1. State transition diagram of the CAS signal detector. Legend: off_hook - initial off hook state, mute off_hook - Off-Hook and local speaker mute state, init FSK - initial state for FSK Caller ID transmission, nbit(win) - the function that returns the number of detections in current window, nb_det - number of set bits in current window that activate detection, false_det - false detection appeared, true_det - true detection appeared.

7.1. Simulation analysis of the IEEE 1390 signal detection

As outcome of the simulation analysis, the tables that contain percentage of successful IEEE 1390 signal detection, for various types of signal distortion and different environmental conditions (no noise case, presence of Gaussian noise, impulse and burst impulse noise), and for both of the frequency sets (low and high), have been constructed.

The main problem, that appears for the low frequencies from simulation results, is the problem of detecting correct alert tone when frequency shift is present. Since the low frequencies are close to each other, frequency shift of 1% may cause a neighboring frequency to be detected as well. For this case not to appear, in order to prevent false detection, decision threshold should be chosen high enough. On the other hand, relatively large decision threshold may prevent amplitude-distorted frequencies from being detected.

M	Sb	Lb	fs	Id	A	F	I	AFI
	8	8	8000	100	100	97.626	100	90.801
			10000	100	100	98.516	100	92.582
	4	4	8000	100	100	98.516	100	91.988
			10000	100	100	98.516	100	90.208
	3	3	8000	100	100	100	100	88.427
DMF			10000	100	100	99.703	100	92.582
	3	2	8000	100	100	93.175	100	81.899
			10000	100	100	96.142	100	79.228
	2	3	8000	100	100	96.439	100	82.493
			10000	100	100	96.406	100	86.647
	2	2	8000	100	100	87.834	100	77.448
			10000	100	100	98.516	100	82.789
	4	1	8000	100	100	95.846	100	81.602
			10000	100	100	98.220	100	92.878
SAS	3	1	8000	100	100	100	100	89.911
			10000	100	100	100	100	84.866
	2	1	8000	100	100	92.285	100	80.119
			10000	100	100	99.406	100	78.635
	1	4	8000	100	100	100	100	100
			10000	100	100	100	100	100
WPD	1	3	8000	100	100	97.033	100	99.110
			10000	100	100	97.703	100	99.703
	1	2	8000	100	100	95.252	100	96.736
			10000	100	100	99.406	100	98.813
BMF	1	1	8000	100	100	99.406	100	99.109
			10000	100	100	100	100	99.109

Table 1. Percentage of Successful IEEE 1390 Signal Detection: Low Frequency Tone Alerts; Impulse Noise. Legend: M - Detection Method, Sb - number of Input Signal bits, Lb - number of Local Signal bits, fs - sampling frequency, Id - Ideal conditions, A - Amplitude distortion, F - Frequency shift, I - Interference signal, AFI - Presence of all AFI distortions.

In the case of the high frequencies, all of the methods show satisfactory performance (the distance is large compared to the allowed shift). A suboptimal method selected for the low frequency signal detection, can be used for the high frequency signal detection as well.

Based on simulation results (Table 1 shows simulation results for the low frequency set, for one of simulated environment cases), and having in mind that low sensitivity to frequency shift is of the greatest importance, BMF and WPD detection methods are chosen for implementation. The decision threshold for both of the selected methods is shown to be adjustable.

7.2. Simulation analysis of the CAS detection

The detection technique applied to the CAS signal detection is the discrete correlation of input and local signal functions. Since considerable frequency shift of 1% of nominal frequency values is allowed, five correlators for each one of CAS frequencies are assumed.

After the detection cycle is finished, the results of these correlation functions are summed in order to provide the value that is compared to the decision threshold. The result of this comparison is stored in the shift register (a window through which M last detection results were seen). If this window contains N set bits, the

M	Sb	Lb	fs	N	Id	A	F	AF	FA
				160	100	100	100	100	7.418
			8000	120	100	100	100	100	7.418
	10	10		80	100	100	100	100	5.341
				200	100	100	100	100	1.187
			10000	150	100	100	100	100	6.528
				100	100	100	100	100	8.605
				160	100	100	100	100	7.715
			8000	120	100	100	100	100	5.638
	8	8		80	100	100	100	100	6.528
				200	100	100	100	100	9.792
			10000	150	100	100	100	100	5.935
				100	100	100	100	100	5.044
				160	100	100	100	99.675	0.890
			8000	120	100	100	100	100	7.418
	4	4		80	100	99.675	99.675	97.074	0.594
DMF				200	100	100	100	100	1.780
			10000	150	100	100	100	100	6.232
				100	100	100	100	100	0.594
				120	100	100	100	100	5.044
	3	3	8000	80	100	100	99.675	99.675	1.484
				150	100	100	100	100	10.385
			10000	100	99.703	99.351	100	100	0.297
				120	100	100	100	100	6.232
	3	2	8000	80	100	99.673	100	100	17.211
				150	100	100	100	100	7.122
			10000	100	100	100	100	100	2.077
				160	100	100	100	98.048	2.967
			8000	120	99.703	100	99.673	99.351	1.780
	8	1		80	99.703	100	98.692	96.087	0.890
				200	100	100	100	100	0.593
			10000	150	100	100	100	100	4.747
SAS				100	100	100	100	100	2.967
				160	100	100	97.725	94.152	0
			8000	120	100	100	99.675	100	5.341
	6	1		80	99.703	100	98.041	95.450	0.593
				200	100	100	99.351	99.351	0
			10000	150	100	100	100	100	2.374
				100	100	100	100	100	2.967

Table 2. Percentage of Successful CAS Signal Detection: Off-Hook Detection - Ideal Filter Case. Legend: M - Detection Method, Sb - number of Input Signal bits, Lb - number of Local Signal bits, fs - sampling frequency, Id - Ideal conditions, A - Amplitude distortion, F - Frequency shift, AF - Presence of all AF distortions, FA - percentage of false alerts suppressed by muting the local speaker.

detector changes its state and performes the mute interval detection, in order to avoid false alerts. During the mute interval, only one detection cycle is performed and the final decision is made. Since the number of input bits is of great importance, and CAS signal may be buried deep in noise (voice), we have excluded WPD and BMF suboptimal detection methods from further observation.

The main problem that appears during the CAS signal detection is the problem of false alerts and how to avoid them. The voice can trigger muting rather than CAS, which means that a certain number of mute intervals will be generated unnecessarily. Since 90% of voice average spectral power is concentrated below 2kHz [10], one can decide to include an analogue filter to filter out the voice below 2kHz, which can significantly lower the percentage of false alerts, as it can be seen from Table 2.

Based on the simulation results, DMF88 and SAS81 suboptimal detection methods have been chosen for implementation of the CAS signal detector: The complexity of the implementation based on DMF88 is not the lowest, but the detection algorithm may be successfully performed by the appropriate digital signal processor; The main interest for SAS81 method lies in the fact that it needs only 1 bit per local signal sample and thus, offers a low complexity solution.

8. Implementation analysis

The major goal of the implementation analysis is to estimate the gate count (transistor count) necessary for implementation, and to form a synthesizable (silicon-compiler-ready) VHDL model of suboptimal detection methods selected for implementation.

8.1. Gate-level schematics

The hierarchical gate-level schematics, developed during the analysis, present our solutions to the signal detection problem of interest, for the selected suboptimal detection methods. Transistor count estimate is based on the one-transistor-per-ROM-bit rule and the CMOS rule-of-thumb, 2X + N, where X refers to the number of inputs and N is usually equal to 0.

The detector core of SAT/DAT signal detector is shown in Figure 2. With respect to the signes of the input samples, and to the contents of the local memory (contains values of local signal samples), detector core performs appropriate operations by the use of its arithmetical and logical resources. Temporary values for detection in progress, for every of the frequencies, are kept in the register files. At the end of the detection cycle, register files contain final values, which are then used by the output module for further processing. After comparison with the detection threshold a decision is made, which of the frequencies are present at the circuit's input. The output logic generates final results of detection and provides an interface to other TIU elements.

Based on the hierarchical gate-level schematics, the maximal implementation complexity of the SAT/DAT signal detector has been estimated: a) 8000 gates for detector core without local memory, and the total of 165500 transistors, altogether with local memory, in the case of BMF detection method; b) 9500 gates for the detector core without local memory, and the total of 572000 transistors, altogether with local memory, in the case of WPD detection method.

Based on the hierarchical gate-level schematics, the maximal implementation complexity of the CAS signal detector has been estimated: a) 8000 gates for detector core without local memory, and the total of 36000 transistors, altogether with local memory, in the case of SAS detection method; b) 11000 gates for the detector core without local memory, and the total of 76000 transistors, altogether with local memory, in the case of DMF detection method.

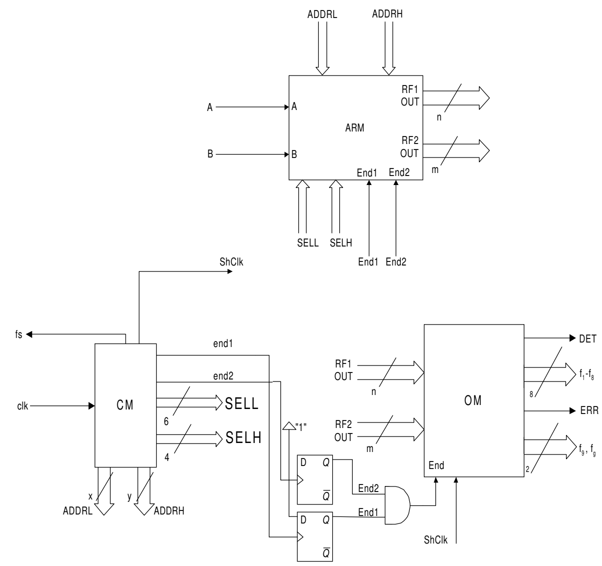

Figure 2: The Core Detector (DetCore) Legend: ARM – adder, registers and memory, CM – control module, OM – output module, SELL, SELH – low and high register file selection signals, respectively, ADDRL, ADDRH – low and high local memory addresses, respectively, x, y – width of ADDRL and ADDRH respectively, End1, End2 – indicators of end of processing for low and high frequencies respectively, A, B, low and high input bits, respectively, fs – sampling frequency, clk – input clock, ShClk – shift register control signal.

8.2. VHDL modeling and silicon compilation

The existing approaches to VLSI design are usually: (a) full-custom, (b) standard-cell, gate array, or programmable logic, and/or (c) silicon compilation in the form of either C-to-silicon or HDL-to-silicon. In this approach, the design is described using high-level language (VHDL) following the silicon compilation rules [11], since not all of VHDL is synthesizable. The HDL-to-silicon approach has been chosen, since it is widely accepted among the leading silicon die manufacturers, and is expected to become a standard of future designs [12]. VHDL data-flow model is obligatory for todays synthesis tools, and the final form of the design should conform to this request.

Structural and behavioural descriptions of model entities are used, in order to test the design concepts and prove design feasibility, hiding, at that phase, unnecessary details. In further steps of refinement, when preparing the model to synthesis, behavioural descriptions are changed to the appropriate data-flow descriptions, allowing for silicon compiler to perform its task, while structural descriptions remain unchanged.

```
-- CAS signal detector core
use work.CASpack.all;
entity DetCore is
   port ( CLK, START, EoC, RESET: in bit;
              FS, CAS, MUTE: out bit;
               A: in bit_vector (7 downto 0)
   );
end DetCore;

-- Structural description of DetCore
architecture Structure of DetCore is
-- Signals declaration
   signal ENDSIG, SHCLK, T: bit;
   signal SEL: bit_vector (5 downto 0);
   signal RFIN, RFOUT: bit_vector (NREG downto 0);
   signal ADDR: bit_vector (NADDR downto 0);
   signal BUFFOUT, MEMOUT: bit_vector (7 downto 0);
   signal MULOUT: bit_vector (15 downto 0);

-- DetCore component declarations:
-- InBuffer, Multiplier, Adder, Memory, RegFile,
-- ControlModule,and OutputModule
-- ...

-- Structure of DetCore body

begin
   CM: ControlModule
       port map (CLK, RESET, ENDSIG, SHCLK, FS, T, ADDR, SEL);
   BF: InBuffer
       port map (Eoc, RESET, A, BUFFOUT);
   MUL: Multiplier
          port map (BUFFOUT, MEMOUT, MULOUT);
   ADD: Adder
          port map (MULOUT, RFOUT, RFIN);
   MEM: Memory
          port map (ADDR, MEMOUT);
   RF: RegFile
       port map (RESET, RFIN, SEL, RFOUT);
   OM: OutputModule
       port map (ENDSIG, START, SHCLK, T,
              RESET, CAS, MUTE, SEL);
end Structure;
```

The above shown VHDL code represents structural description of CAS detector core, together with declarations of the components that the core consists of. The behavioural description of these components are used in the early design stages, and further structured and changed with data-flow descriptions at the end design stages.

9. Conclusion

Suboptimal detection methods have been adapted to the particular problem, and an exhaustive simulation analysis has been performed and various suboptimal detection methods compared by the means of their applicability to the IEEE 1390 signal and the CAS signal detection. It was shown that suboptimal detection methods are generally applicable to the IEEE 1390 signals and the CAS signal detection problems. As a final step of this research, the gate-level schematics were developed for candidate solutions (selected after the simulation analysis was completed), in order to estimate implementation complexity. Transistor count estimates are given for all suggested solutions. The next final logical step was to do a production-level model using synthesizable portions of VHDL, to serve as input to a silicon compilation.

Interested VLSI designers and architects involved in signal detection and special purpose chip design may benefit from this research. A design that implements suboptimal detection methods would increase the performance/complexity ratio, compared to the optimal detection methods implementation. The careful achievement of a tradeoff leads to a design with the optimal performance/complexity ratio, which may be of greatest importance if VLSI implementation of the design is the primary intention.

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