

RAPID RADIO: A FRAMEWORK FOR HUMAN-ASSISTED SIGNAL CLASSIFICATION AND RECEIVER IMPLEMENTATION

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Abstract—An analysis-based framework for the rapid development of a radio receiver for signals with unknown parameters is proposed, exploiting the reconfiguration capabilities of FPGAs. The framework guides a non-expert user through the process of signal classification and FPGA-based receiver implementation. System efficiency is traded off with implementation time in order to allow fast radio creation. A set of high-level transformations are applied to the unknown signal based on different hypothesis about the modulation scheme. The results of the transformations are presented to the user, who can steer the process of analysis. The parameters of the radio are then mapped by means of an Implementation Engine to modules implemented in a general purpose FPGA-based receiver.

I. INTRODUCTION

There are many circumstances when a signal intelligence expert is faced with the need to quickly extract data from an otherwise unknown signal, but lacks the knowledge of how the signal was modulated. The traditional approach to this would be to go through an analysis phase to construct a hypothesis of the signal's modulation parameters, and then enter a design phase to create the required custom radio receiver. This process is a slow progression of steps from signal analysis, receiver modeling, receiver design, to prototyping. This process mimics the traditional approach towards radio receiver design where a fairly efficient radio is ultimately realized. Efficiency is usually measured in terms of hardware resources used, such as gates and multipliers, or power consumption. With the progression of technology, many of these metrics are outdated or even meaningless when instant gratification is needed. For example, minimizing the number of multipliers may be moot if the target platform contains multiple FPGAs with thousands of otherwise unused multipliers is available. If the speed of deployment is paramount, and the prototyping platform has an abundance of resources, then the design process can be altered in a way to produce an operational yet possibly suboptimal receiver in a short time. In this paper we present an analysis-based approach to receiver implementation called the Rapid Radio framework. This framework is a human-guided framework that provides the user with the required tool set for classifying an unknown signal and creating an FPGA-based implementation

of the receiver. The analysis of a signal is broken down into several steps where high-level transforms are applied to the signal. At each step, variations of a given transform are applied to the signal, the results of which are shown to the user via a graphical user interface (GUI) and a series of metrics. With the provided information, the user can choose which of the transforms is correct. By choosing the correct transform, the user is in essence defining the receiver architecture. The results of the chosen transform are then used as the input to other transforms. For example once timing recovery has been accomplished, a series of different Phase-Locked Loops (PLLs) are applied to the signal and the resulting constellations are shown to the user. The user can then choose which constellation looks correct. After the necessary transforms have been applied and the symbols have been identified, a Radio Description File (RDF) is created detailing the modules required for the receiver based on the transforms applied to the signal. An all digital, FPGA-based implementation of the receiver is then provided to the user.

II. RELATED WORK

A great amount of effort has been devoted to the problem of automatic modulation classification (AMC). In [1], the author presents a comprehensive overview of the state of the art in the field, and presents a broad classification of AMC algorithms as likelihood based (LB) and feature based (FB). Cyclostationary techniques to classification are presented in [2]. Approaches directed towards the implementation of actual radios based in multiple features are presented in [3] and [4]. In particular, they explore the use of the quasi-baseband signal obtained after down-conversion, which is readily available in a combined radio implementation/modulation classification approach. The Rapid Radio framework builds on top of the tools and techniques developed from the AMC field to allow a user to analyze an unknown signal and create an FPGA based implementation.

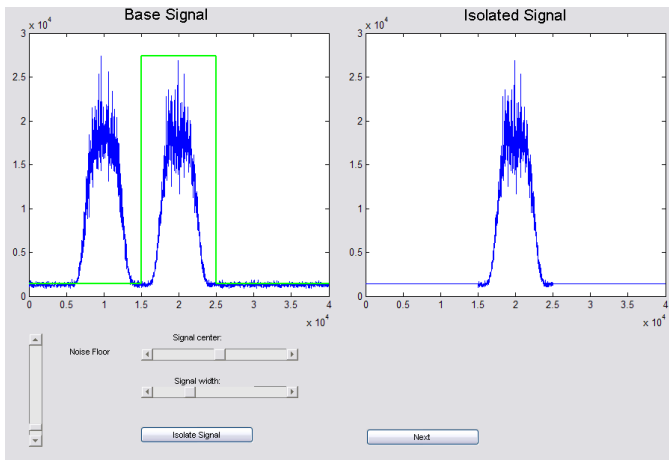


Fig. 1. GUI for input signal isolation

III. PROPOSED FRAMEWORK

The Rapid Radio framework is an analysis tool that directly leads to the creation of a rapid prototype of a receiver. Similar to other analysis tools, it designed to aid the user in the classification of an unknown radio signal. The unique aspect of this framework is that the radio architecture description is generated by the tool as a result of a guided analysis process. This process abstracts away much of the knowledge required by the process of radio design and implementation.

Due to the complex nature of signal classification a "human in the loop" approach is used in the Rapid Radio framework. Instead of attempting a full automatic classification of the signal, the framework presents the results of the intermediate tests to the user, allowing the user to steer the identification and radio implementation processes. The framework is to be initially tested over the phase/amplitude digital modulation family of signals and will have a Matlab front end.

Currently the framework consists of the following five major transformation types:

- 1) Signal identification and isolation
- 2) Modulation parameter estimation
- 3) Symbol timing recovery
- 4) Constellation identification
- 5) Symbol mapping

A. Signal Identification and Isolation

The frequency band of interest must be selected by the user in order to eliminate any other signals present in the spectrum that may interfere with the signal classification process. Figure 1 shows the GUI used for signal isolation. A periodogram of the captured spectrum is shown to the user. Using the scrollbars at the bottom left, the user selects the area on which further processing will be done. Because eliminating all noise in this transform would negatively affect the spectral fitting performed later, no filtering is done. Instead, the area of the periodogram not belonging to the signal is replaced with a fixed value that represent the noise floor. This replacement is shown on the left side of Figure 1.

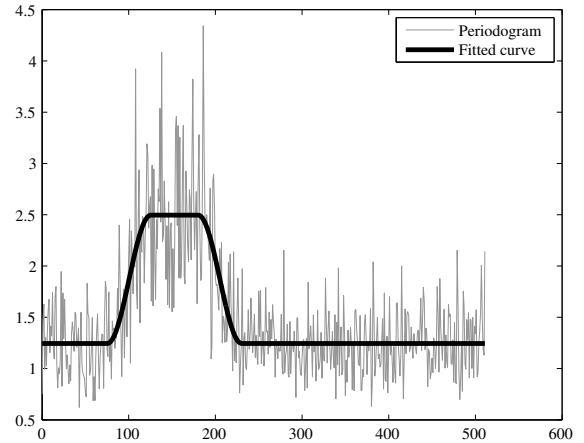


Fig. 2. Spectral fitting of QPSK signal

B. Modulation Parameter Estimation

A modulation parameter estimator in the frequency domain is achieved by fitting an analytic description of the spectral shape of the signal. Based on user input of likely modulation formats, several spectral fittings are applied to the isolated signal power spectrum. The fitting is then presented to the user. For linear amplitude/phase modulations, if the transmitted pulse has a square root of raised cosine pulse shape, the power spectrum will have a raised cosine spectral shape, which has a non-linear dependence on the parameters f_c , f_{sym} , and α . Use of the un-smoothed periodogram is required to avoid bias in the estimate of the roll-off factor α . A non-linear optimization method is to be applied to find the least square error fitting of the spectral shape. The dogleg method [5] allows for a computationally inexpensive solution to the problem. An example display of a fitting under the square root of raised cosine hypothesis is presented in Figure 2.

Using the estimated modulation parameters \hat{f}_c , \hat{f}_{sym} and $\hat{\alpha}$, the signal's bandwidth can be estimated and an isolation band-pass filter is synthesized and applied to the signal. The estimate of the desired signal's center frequency is used to down-convert it to baseband. Lastly a matched baseband filter is created based on the estimated parameters and applied to the baseband signal.

C. Symbol Timing Recovery

In order to synchronize a signal with a high degree of uncertainty around its nominal symbol rate, a high frequency offset robust symbol synchronizer was implemented. A modification to the Gardner timing error detector presented in [6] is proposed in order to obtain a normalization of the timing error measurement, which requires four vector samples per symbol. The baseband signal is therefore re-sampled at $4 \cdot \hat{f}_{sym}$ to obtain the four samples per symbol required by the algorithm. Because the modification preserves the rotation invariance of the Gardner detector, posterior carrier recovery is possible. Figure 3 presents a simplified diagram of samples

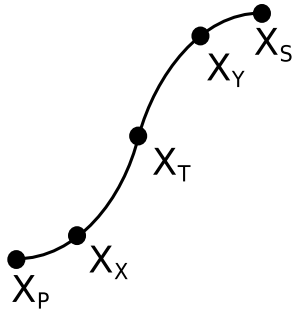


Fig. 3. Sampling for timing error detector.

at a symbol boundary: X_P represents the strobe sample at the previous symbol. X_T represents the timing measurement sample. X_S represents the next strobe sample. X_X and X_Y are auxiliary samples required for normalization. The samples are represented by 2×1 vectors denoting the sample's coordinates in the I-Q plane.

If we assume that X_X , X_T , and X_Y lie on a straight line, then the normalized timing error measurement is given by Equation 1:

$$\tau = \frac{1}{2} \frac{\langle X_T, d \rangle}{\|d\|^2} \quad (1)$$

Where $d = X_Y - X_X$. This timing error measurement is normalized symbol interval units. Therefore, a value of $\tau > 1/8$ indicates that a fill operation is required (make $X_S = X_Y$, and advance three samples); a value $\tau < 1/8$ indicates that a skip is required (ignore strobe and advance one sample). Otherwise, coarse timing is accepted and timing is shifted by four samples to the next symbol. In all cases, a polyphase filter adjusted by the value of τ is required to interpolate the signal at the optimum sampling instant.

The timing error measurement can only be applied when a transition between different symbols occurs and is prone to self-noise which is aggravated by the construction of the receiver's matched filter based on inexact estimates. Therefore, a tracking algorithm must be included in order to follow the symbol timing. A Kalman filter based on a frequency and phase state model of the sampling offset relative to the symbol timing is used to predict the symbol timing when a measurement is unavailable. The model is updated when actual measurements are performed. A clear advantage of the Kalman filter approach is that the value of the state variable for the frequency offset can be used to refine the initial symbol rate estimate.

The results of these transformations are shown to the user in order to confirm convergence of the estimators (i.e.: assessment of an eye diagram is a useful tool to test sampling time correctness). Constellation points prone to carrier frequency error (rotating) are presented to the next stage.

D. Constellation Identification

The problems of de-rotation and constellation test are interdependent, as no hypothesis on the constellation can be tested without de-rotation; and vice versa: no de-rotation is

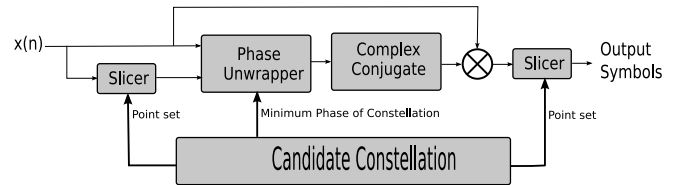


Fig. 4. Symbol de-rotation

possible if the constellation is unknown [3]. A joint method based in successive de-rotation, evaluation of the likelihood of the hypothesized constellations given the quasi-baseband sequence, and evaluation of the likelihood of the quasi-baseband sequence given the hypothesized constellations is proposed.

PLLs are currently used to recover the carrier information; however, as the initial parameters are gross estimates, potential hangup may occur within this approach. A feed-forward approach is proposed, with double application of slicers: a first slicer is applied before phase correction, in order to obtain the phase shift slope inside the decision regions. A non-linear Kalman filter with frequency and phase states is applied to the wrapped phase in order to obtain an unwrapped phase vector. The phase boundaries are determined by the description of the constellation under test. The conjugate phase vector is then multiplied with the rotated symbol sequence in order to achieve de-rotation. Figure 4 illustrates this approach. As in the symbol recovery case, the state vector can be used to refine the initial carrier frequency estimate.

This process is to be performed for every hypothesized constellation. In order to perform a likelihood test for a given constellation, power normalization is required before the de-rotation and hypothesis testing blocks. The likelihood of the constellation is calculated from two measurements to be performed on the system:

- *Constellation error*: Measure the power of the difference of the signals obtained before and after the output slicer. In the case of the true constellation, this measurement corresponds to the additive noise power. The drawback of this measurement is that it does not allow for differentiation of nested constellations.
- *Symbol distribution*: For a given constellation, a relative occurrence of the symbols included in the constellation set is expected at the output slicer. A metric is developed based on the underlying Bernoulli process that is mapped to the constellation points. Differential and Trellis coded modulations are to be tested according to the symbol transition statistics observed at this stage. This measurement fully differentiates nested constellations, and therefore complements the constellation error metric.

An advantage of the presented scheme is that the architecture of the constellation identification block is modulation independent, and only requires the input of the constellation description, consisting on the set of points, the absolute

probability of each point and the transition probabilities among the constellation points

E. Symbol Mapping

A library with candidate bit groups to symbol mappings is provided to the user in order to identify symbols. Provision is made for passing the results for further processing, as channel decoding and de-scrambling.

IV. FPGA-BASED IMPLEMENTATION

In addition to aiding the user to classify an unknown signal, the Rapid Radio framework contains an Implementation Engine, which guides the user through the process of generating an FPGA-based implementation of the radio receiver. The Implementation Engine receives as input a Radio Description File (RDF) and a top level Hardware Description File (HDF). The implementation engine's output is a receiver module definition in HDL. Any object files, such as an ngc, required to instantiate the module in the target platform will also be provided.

A. Radio Description File

The Radio Description File contains the list of all modules required for the receiver and how they are connected. The RDF is constructed from the list of transforms applied to the signal at analysis time. Because of its structured format and the large number of parsing libraries available, eXtensible Markup Language (XML) will be used for the RDF. A new XML schema called *RapidRadio* was created to define the syntax of the RDF. Figure 5 shows the various elements of the radio description file. Module instantiations in the RDF, shown in Figure 5(a), consist of the *Name* tag (which must be unique), the *Type* and *Subtype* tags, the *Interface* element that defines high-level ports, and the *Parameter* tag that contains any type-specific parameters. Because the module's ports are implementation-dependent, they are not known at analysis-time, therefore only a high-level definition of the modules interface is provided.

The *Parameter* element defines attributes of the module which are specific to its type or subtype. A band-pass FIR filter, for example, will have its center frequency, bandwidth and transition band width as parameters, whereas a complex mixer would have the mixing frequency. The use of the *Parameter* element is shown in Figure 5(a).

A list of *Connection* elements included in the RDF are used to define connections between modules. These specify how the module interfaces interconnect through the use of the *Sink* and *Source* elements. The *Source* element contains the name of the source module and interface. The *Sink* element contains the name of the destination module and interface. Multiple *Sink* elements can be used to specify a multi-sink connection. Figure 5(b) shows the instantiation of several connections.

Interfaces for the overall receiver module are defined with the *ReceiverInterface* element. This is shown in Figure 5(c). A module name of *Global* is used in the *Sink* and *Source*

```
- <rr:ModuleInstance Name="IsoFilt" Subtype="Bandpass" Type="Filter">
  <Parameter Name="SamplingFreq" Value="80000.00" />
  <Parameter Name="CenterFrequency" Value="19988.00" />
  <Parameter Name="Bandwidth" Value="7799.00" />
  <Parameter Name="TRbandwidth" Value="390.00" />
  <Interface Direction="input" Name="DataIn" />
  <Interface Direction="output" Name="DataOut" />
</rr:ModuleInstance>
- <rr:ModuleInstance Name="Mixer" Subtype="rrcos" Type="ComplexMixer">
  <Parameter Name="alpha" Value="0.60" />
  <Parameter Name="SamplingFreq" Value="80000.00" />
  <Interface Direction="input" Name="DataIn" />
  <Interface Direction="output" Name="I_Out" />
  <Interface Direction="output" Name="Q_Out" />
</rr:ModuleInstance>
```

(a) Module instantiations

```
- <rr:Connection>
  <Source Interface="RFIn" Module="Global" />
  <Sink Interface="DataIn" Module="IsoFilt" />
</rr:Connection>
- <rr:Connection>
  <Source Interface="DataOut" Module="IsoFilt" />
  <Sink Interface="DataIn" Module="Mixer" />
</rr:Connection>
- <rr:Connection>
  <Source Interface="I_Out" Module="Mixer" />
  <Sink Interface="I_In" Module="Resampler" />
</rr:Connection>
- <rr:Connection>
  <Source Interface="Q_Out" Module="Mixer" />
  <Sink Interface="Q_In" Module="Resampler" />
</rr:Connection>
```

(b) Interface connection definitions

```
<rr:ReceiverInterface Direction="input" Name="RFIn" />
<rr:ReceiverInterface Direction="output" Name="BitsOut" />
```

(c) Receiver module interface

Fig. 5. Radio Description File elements

elements to indicate that the interface does not belong to an instantiated module, but to the overall Receiver.

Storing the results of signal classification in the RDF separates signal classification process from the receiver implementation processes. This separation allows for the quick re-implementation of receivers for previously identified signals.

B. Hardware Description File

The Hardware Description File consists of platform specific information required for the implementation of the receiver, such as the system clock frequency, the location of a top level HDL file and the FPGA vendor and model. The top level HDL must include any logic necessary to obtain the input data, such as ADC initialization and administration, as well as what to do with the data produced by the receiver. This allows the generation of the receiver to be platform independent.

C. Module Generation and System Assembly

Hardware modules required for the generation of the radio will be either originate from a library of implementation independent modules or they will be automatically generated.

The library will contain all modules necessary to support the available transform and their variations or instructions on how to automatically generate them. A module description file, attached to each module describes the specifics of the modules implementation. The file also indicates the modules interface type and how the interface maps to its ports. A given interface can be mapped to one or more ports of varying directions. The input interface for Coregen generated filters, for example, is mapped to three ports: the dataIn bus (input), the NewData signal (input) and the ReadyForData signal (output).

Implementation dependent modules, such as FIR filters used during down-conversion will be generated at implementation time using vendor tools such as Xilinx's Coregen. All generated modules will be then added to the library for use in future implementations. When a suitable implementation has been found for all required modules, a receiver module is assembled by the implementation engine.

Because all transforms are mapped to self-contained modules, system assembly mainly consists of module instantiations and communication synthesis. Instantiating modules is a trivial task and mainly consists of basic string processing.

Communication synthesis on the other hand is not as trivial. To enable the automatic creation of connections between two interfaces programmatically a set of interconnection rules must be defined. These rules define how to create connections between the ports of two interfaces. For any given interface type a rule must exist defining how to connect it to other interfaces types. The interface definitions and the interconnections rules will be stored in an XML schema base on the technologies presented in [7] and [8].

Because of the varying styles of communications used by interfaces, interconnecting two interfaces may require more than just creating wires between ports. For example, let's consider connecting a block-based interface with a stream-based interface. Upon receiving the ready for data signal a block-based interface will send N data words to the receiver, where N is a known constant. In a stream-based interface the sender will only send one data word per ready for data signal. To create a connection between these two interfaces, a bridge module with a FIFO and some control logic needs to be inserted. Any glue logic needed, such as the FIFO mentioned above will be integrated into the interconnection rules. The FPGA configuration bitstream is the created from the top-level system provided in the HDF and the radio module and objects provided by the implementation engine. A vendor specific makefile is used to invoke vendor tools.

V. CONCLUSIONS

A Rapid Radio framework based on a guided process for radio signal analysis was presented. The user applies transforms to the signal and is presented with the results. In accepting or rejecting the transform, the user is defining the architecture of the radio. After all transforms have been applied, a Radio Description File is created detailing the architecture of the receiver.

Information extracted about the unknown signal is used with the Hardware Description File to build an FPGA-based radio receiver. A communication synthesis scheme is used to connect modules of different interfaces. The design of both the radio and hardware description files must be such that they avoid dependence on specific vendors.

Hardware efficiency is traded off with implementation time in order to allow a fast radio creation over a general purpose hardware platform. Providing high-level transforms to aid in classifying a signal eliminates the need for detailed communications knowledge by the user. The combination of pre-built modules, automatic module generation and communication synthesis reduces the burden of HDL development and in-depth knowledge of FPGAs. Support for other modulation families can be added by implementing new transforms.

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