Design and Development of Phasor Measurement Unit and it's compliance testing using mini-FSS

Submitted in partial fulfillment of the requirements

for the degree of

MASTER OF TECHNOLOGY

(Power Electronics & Power Systems)

by

AUTHOR'S NAME

(AUTHOR'S ROLL NO.)

under the guidance of

Guide's Name

Department of Electrical Engineering

INDIAN INSTITUTE OF TECHNOLOGY BOMBAY

June 2016

Dedicated to

Whomsoever You Want To

Dissertation Approval Certificate

This dissertation entitled **Thesis Title** by **AUTHOR NAME** (Roll No: AUTHOR'S ROLL NO.) is approved for the degree of **Master of Technology** in Electrical Engineering with specialization in **Power Electronics and Power Systems** from **Indian Institute of Technology Bombay**, India.

Examiners

_____

_____

Supervisor

_____

Chairman

_____

Date:_____

Place: _____

Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

AUTHOR NAME

AUTHOR's ROLL NO.

Department of EE

IIT BOMBAY

– June 2016. **CHANGE THIS**

Acknowledgement

Write your acknowledgements here

AUTHOR NAME

Abstract

Write your abstract here

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Electric energy has become one of the most important source of energy and is widely used resource in world, with ever increasing demand of (any) resource it becomes more and more difficult to maintain the system and Power System is no exception. Power System has become a complex entity and has gone beyond the limit of manual operation and control, which makes automation and "smart" control imperative. This creates demand for new set of measurement, operation and control tools. Out of these tools measurement tools are the most fundamental building block of the modern power system, which is now also know as "smart grid". Measurement devices are "eyes" and "ears" in the system to the centralized "brain", operating-control-corrective system.

In power system active power and frequency are the most important parameters to be monitored, flow of active power is decided by the phase angle of voltage between buses. Flow of active power decides the structure of network (transmission lines, capacity of devices etc) and hence accurate measurement of it has been of great interest since 1960-70s.[2]. Conventionally *relative phase difference* between buses in the network was used, due to limitation of communication links, computational power and the economic pheasibility. This method(s) were slow, moderately accurate and dependent on a tones of heavy and/or manual calcualtion. After advancements in telecommunition technology and their speed & reliability, better computation and satelite availability, trend of *absolute phase difference* measurement came in to existance [3]. The earliest system using absolute phase difference was reported in 1980 using LORAN-C satellite and HBG radio transmission for time reference. And during the same period Global Positioning System was being implemented by US DoD, which was immediately recognised as one of the best

way of synchronising the power system, which brought the "Phasor Measurement" and "Synchrophasor" era in to existance. Lot of research was carried out and is being carried out in this area, and flurry of papers are available and are being published in different aspect of synchrophasor measurement.

1.1 Phasors, Synchrophasors and PMUs

1.1.1 Phasors: Defination

In 1893 C. Steinmetz in his paper introduced simplified mathematcal description of a waveform of an alternating current electricity which he called as "phasor". In Physics and Engineering, *phasor* is a complex number representing a sinusoidal quantity whose amplitude (A), angular velocity (ω) and initial phase (ϕ) are time-invarient.It is an analytic representation which decomposes sine function in to product of complex constants and a factor which encapsulates the frequency and time dependence. he complex constant, which encapsulates amplitude and phase dependence, is known as phasor, complex amplitude, and (in older texts) sinorx or even complexor.

Which Using Euler's formula can be represented mathematically as:

$$\boldsymbol{Ae^{i(\omega t+\theta)} = A\cos(\omega t+\theta) + A\sin(\omega t+\theta)} \tag{1.1}$$

1.1.2 Synchronised Phasors or Synchrophasors

Synchronized sampling/measurement of sinusoidal complex quantity (phasor) at a precise reference (time) is called Synchronised Phasor. Time synchronization (of samples) allows

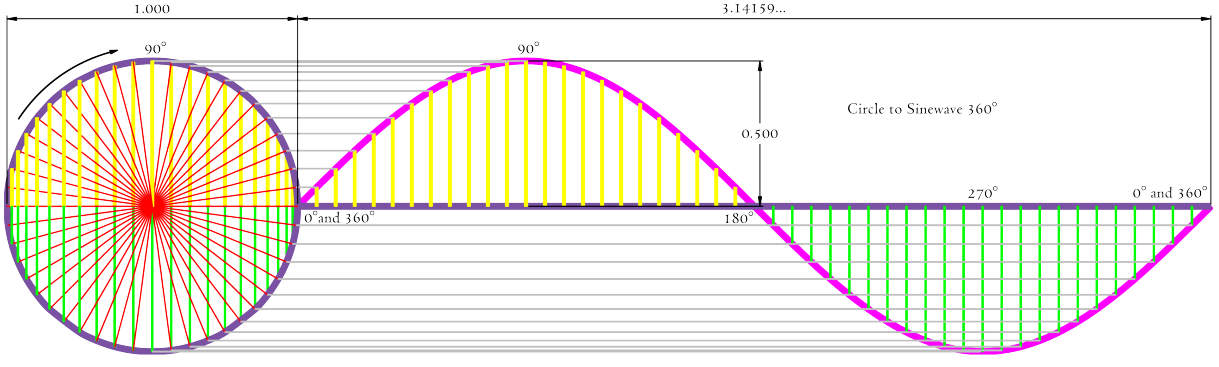

Figure 1.1: Phasor Representation, Sampling and synchrophasor [1] .

synchronized real-time measurements of multiple remote location measurement points on the grid. And this resulting measurement is know as **synchrophasors** Fig. 1.1.

1.1.3 Phasor Measurement Unit (PMU)

PMU is a device which measures and estimates electrical wave in an power network using a common time source for sample synchronization. But it is important to note here that it is an "estimate" of the phasor(!!) and not the actual measurement.

This device was first invented by Dr. A. G. Phadke and Dr. James Thorp at Virginia Tech which is considered to be the first successful utilization of "phasors" for real-time phasors measurement that were synchronised with accurate absolute time reference provided by GPS.

1.2 Wide Area Measurements

Classically operation of grid was done by Supervisory Control And Data Acquisition(SCADA) system , which uses state estimator and other iterative solvers on system snapshot every 7-15 mins to measure and estimate the system operating point and phase angles. This approach is rather slow and less accurate but now after maturing of synchrophasor; Wide area monitoring systems (WAMS) have come in to existence, which are essentially based on the new data acquisition method of phasor estimation and allow monitoring of transmission system conditions over large areas and enable detecting and further counteracting grid instabilities. Importance and significance of synchrophasors and PMUs in WAMS can be understood when we see it from a practical perspective. Consider two geographically distant places like in India Kashmir and kaniyakumari or Aasam and Mumbai, How can we compute the phase difference of these two locations? if we want to scale the problem even further we can take American power grid where there exists Time Zone difference of 3 Hours (UTC-8.00 to UTC-5.00) from east coast to west coast, how can this be accomplished? This is where PMU and GPS comes into play, GPS enabled PMU provides an absolute time referenced [1] voltage amplitude, angle and frequency (and maybe few other relevant) data of different bus to a regional control centre and eventually a central main

[1] `http://www.physics.org/article-questions.asp?id=55`

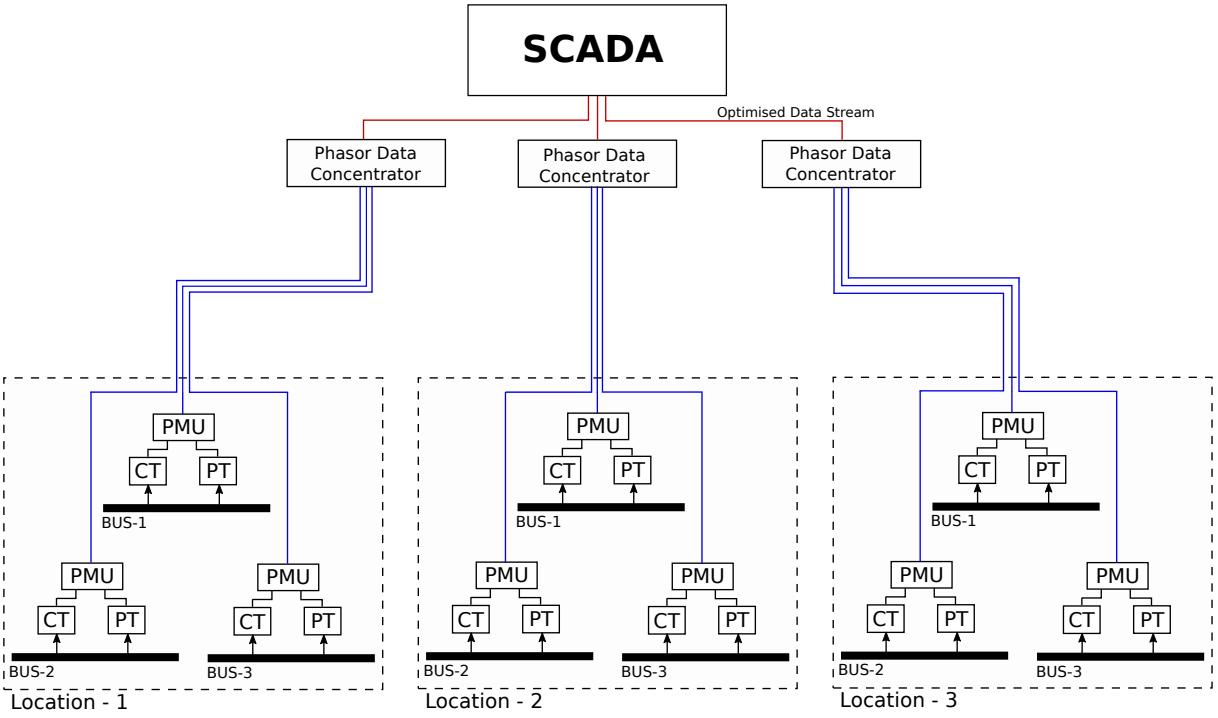

Figure 1.2: Simplified structure of WAMS

control centre/system, this data samples are at a global reference (UTC, usually)[2]. with an accuracy of few microseconds. All of this is available to the control centre at an rate of 12 to 25 snapshots per seconds, such high (and accurate) data (rate) enables system operator to operate the system efficiently and nearer to the operating limits and in case of contingencies enables them to take rapid corrective and/or preventive actions.

Fig. 1.2 Shows a simplified architecture of modern Wide Area Measurement System. PMUs are installed at different substations on HV buses, via CTs and PTs, each PMU has multiple channels sampling AC waves at high rate. Rate of sampling varies according to the manufacturer and implementation of the scheme. Each PMU is provided a GPS receiver for accurate time with accuracy of approx 500 600 ns which is necessary for achieving time accuracy of 1-2 μs demanded by the standard. Each data after being sampled is then filtered using different DFT/FFT algorithm and is timestamped. This time stamped data is then sent to either SCADA or to a local Phasor Data Concentrator, which consolidates the data stream coming from different PMUs and send an bandwidth optimized data stream to the higher PDC or SCADA.

[2]How accurate is GPS? know more: `http://www.gps.gov/systems/gps/performance/accuracy/`

1.3 IEEE C37.118 Standard

1.3.1 Need of the standard

This standard is for synchrophasor measurement, it defines synchronised phasor and frequency measurement is substation alng with requirements for measurement verification. Role of this standard is that measurements taken complient with and abiding to this standard will be readily accurately usable for power system analysis purposes. Standard achieves this by stating minimum necessary performance requirements of time-tagging, sampling and communication requirements to which a PMU has to adhere.

IEEE 1344-1995 is the original standard which was succeeded by IEEE C37.118-2005. 2005 standard mostly followed equipment manufacturers and the system integrators and was stating performance of steady-state conditions. After the advancements and development in fault analysis dynamic synchrophasors were being used for the control and analysis. which was the major reason of Revision-2011, which was immediately followed by revision 2014 which simplified the stringent norms laid down by it's predecessor.

1.3.2 Definations, acronyms and abbriviations

Before diving in to details lets clear out few useful terminologies for ease of understanding and appreciation of the subject:

Phasor: A complex equivalent of a sinusoidal wave quantity such that the complex modulus is the cosine wave amplitude, and the complex angle (in polar form) is the cosine wave phase angle.

UTC: Its is the time of day at the earth's prime meridian.

ROCOF: It is the measure at which the frequency changes in a given instance of time.

Rate of change of Frequency Error (RFE): The measure of error between the theoretical ROCOF and the measured ROCOF for the given instant of time.

Frame: A data frame or a frame of data is a set of synchrophasor, frequency, and ROCOF measurements that corresponds to the same time stamp.

Anti-aliasing: The process of filtering a signal before sampling to remove components of that signal whose frequency is equal to or greater than the Nyquist frequency (one-half the sample rate). If not removed, these signal components would appear as a lower frequency component (an alias).

Nyquist frequency: A frequency that is one-half the sampling frequency of a discrete signal processing system.

1.3.3 Requirements and Compliance

Just like all other engineering devices PMU's reliability, accuracy and precision are very crucial for its application and hence different kinds of test are done to validate its performance. Hence just like other measuring devices PMU standards are defined which states minimum performance requirement(s). All device should at least meet the requirement stated by the standards, according their application.

Total Vector Error

Classically error is the deviation of the measurement from the ideal quantity. It is computed from the difference between the Actual to the measured value. In case of synchrophasors the comparison involves difference in both amplitude and angle which are time dependent making the task even tougher. these quantities are considered combinely in the standards and is called "Total Vector Error (TVE)" [4].

TVE is an expression of the difference between a "perfect" sample of a theoretical synchrophasor and the estimate given by the unit under test at the same instant of time. The value is normalized and expressed in per unit of the theoretical phasor. Which can be mathematically represented as:

$$TVE(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{X_r(n)^2 + X_i(n)^2}} \tag{1.2}$$

Here $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the estimated values of the given phasor and X_r and X_i are the theoretical values. To be complient with standard, PMU shall provide synchrophasor, frequency, and ROCOF measurements that meet the requirements as per the standards at a given time instance n. Similarly for freq and ROCOF the validation will be done using following equations:

$$FE == |f_{true} - f_{measured}| = |\Delta f_{true} - \Delta f_{measured}| \tag{1.3}$$

$$RFE == |(df/dt)_{true} - (df/dt)_{measured}| \tag{1.4}$$

Class of PMU:

Depending up on the application PMU are classified in two types and depending upon the class their error tolerance is evaluated, there are two classes:

1. **Measurement Class (M):** As the name suggests these are used for measurement and instrumentation purposes. These PMUs are intended for slower response time and greater precision. These kind of PMUs are used for analytical purposes and hence often do not require minimal (reporting) delay or fastest reporting speed.

2. **Protection Class (P):** These PMUs are designed for fastest responses time. They may have (slightly) inferior reporting precision and soft-realtime operation. mandates no explicit filtering

Validation & Testing

To get the TVE, compliance tests are performed and during the test only the quantity under test is varied from the reference condition as per the test and other relevant quantities are maintained at reference condition. There are following kind of compliance tests:

1. Steady-state compliance
    (a) Steady-state synchrophasor measurement requirements
    (b) Steady-state frequency and ROCOF measurement requirements
2. Dynamic compliance
    (a) Synchrophasor measurement bandwidth requirements using modulated test signals
    (b) Ramp of system frequency
    (c) Step changes in phase and magnitude

The TVE tolerance for each case wont be mentioned here as those tables can be looked into the standards.

System Frequency	50 Hz			60 Hz					
Reporting Rate (Fs)	10	25	50	10	12	15	20	30	60

Time Synchronization

The PMU should be capable of receiving time from a reliable and accurate source such as GPS that can provide time traceable to UTC with sufficient accuracy for calculating Total Vector Error (TVE), Frequency Error and rate of change of frequency error (RFE), all measurements are synchronized to UTC. This is a vital parameter because time error of 1μs would result in to 0.022 degree and 0.018 degree in 60 Hz and 50 Hz systems respectively. And a phase error of 0.57deg will result in to 1% TVE. This corresponds to error tolerance of $\pm$26 μs for 60 Hz and $\pm$31 μs for 50 Hz system.

Reporting Rate

Estimate of synchrophasor, Frequency and ROCOF will be made so that they can be reported to data concentrator and the reporting rate should be constant i.e. the time difference between two reports received from a PMU should be same. This reporting rate will be integer number of times per second and should be in integer multiple of the of the power nominal-frequency. Hence required rate of reporting as mentioned below:

Performance Parameters

These are the parameters considered as qualitative factors to judge the PMU performance.

- *Measurement response time:* Measurement response time is the time to transition between two steady-state measurements before and after a step change is applied to the input. This is measured by applying a step change in amplitude or phase and holding the input constant otherwise and measuring the time taken by the PMU to settle to a steady-state value. response time is determined from the accuracy evaluation of the measurements, not step time or the stepped parameters themselves.

- *Measurement delay time:* It is the time difference between the step input applied and the measurement time that the output reaches 50% of the final or steady state value.

- *Measurement Reporting Latency:* Reporting Latency is the time lag between the event occurs in the power system and it is reported in the data. It is one of the important quantitative and qualitative parameter, as it depends on al most all factors involved like sample window, filter delay, processing time, processor speed etc. Here reporting rate and PMU class play major role in deciding the delay.

- *Measurement and operational errors:* It is a self-health-test flag. as per standard PMU should send a status flag with each measurement stating the error at PMU end. this error bit can incorporate issue in any aspect(s) like ADC error, memory over flow, etc.

Communication Compliance

Chapter 2

Implementation

2.1 Requirements and Goals

Depending upon the function we can split the design of a PMU in three parts. A. Signal Input & Sampling part B. Processing of Samples C. Transmission of data Here different parts will have different requirements. So, we will first state the minimum requirement stated by standards or aimed by us.

1. **ADC Requirements** While deciding upon the ADC specification we kept following requirements:

   - Good sampling rate: 64 Samples/cycle
   - No of channels: 3 + 3 = 6 (3 - ϕ voltage and current)
   - Interfacing type: It should be memory addressable and voltage level compatible .
   - Input type: FSS analog output is differential which can be configured as single ended, it's voltage level is $\pm$10V

2. **Processing Requirements** PMU has stringent timing requirement, samples needs to be processed in given deadline of reporting time, for this a processor having good ALU would be preferable, for which DSP core is best suited for rapid low level and hard realtime computation. Normal Discrete Fourier Transform requires of complexity O(N^2) operations hence the computation requirement increases as the sample count increases.

3. **Data Transmission Requirements** Realtime transmission of data is mandated by the standards [4]. For that different protocols like Realtime Media Transfer Protocol (RMTP) or other ways can be used but it would require a sufficiently capable ethernet socket, so we decided to have at least 10/100 MBPs.

2.2 BeagleBone Black

Initially we decided to use TI OMAPL-137 which is a dual asymmetric-core processor, in which one core is of DSP and other one is of ARMv7 a brief description is given in Appendix. Due to a mishap our OMAP L137 stopped working so new processor was chosen. which was AM3359 which is a single core ARM Cortex-A8, 1 GHz processor, we decided to use BeagleBone Black which is an low-coast open source community supported multipurpose board. All hardware design is made available and complete programmatic access to the hardware is given which gives complete flexibility for development and implementation. Simplified technical description of the board is given below:

Processor	
Graphic Engine SGX530 3D, 20M	
SDRAM Mem	
Onboard Flash 4GB, 8-bit Embedded MMC	
Serial Port	
HS USB 2.0 Client ports	
HS USB 2.0 Host Port	
Ethernet	
SD/MMC Connector	
Video Output	
Expansion Connectors	power 5v, 3.3V, VDD_ADC (1.8v) GPIO(69 Pins), I

As we can see, specification are pretty impressive but the most important feature of this board are the PRU-ICSS, Programmable Realtime Units Industrial Communication subsystems. Which are two independent 200Mhz 32bit RISC cores . They operate completely independent from the the ARM core, allowing independent operation and

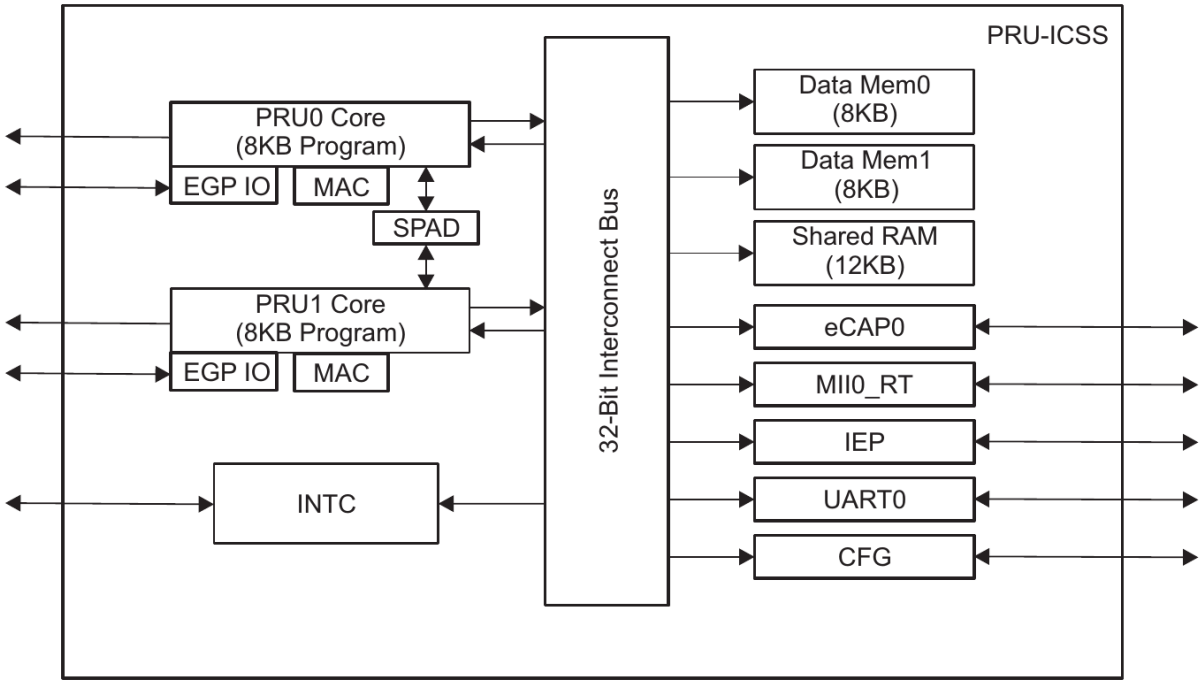

Figure 2.1: Block Diagram of PRU Subsystem

clocking for greater efficiency and flexibility. The PRU-ICSS enables additional peripheral interfaces and real-time protocols. In addition they have fixed execution time, they are connected to (almost) all peripherals with Enhanced Data Bus for (for GPIO for) better communication. PRUs can be programmed separately by loading them with a binary file. Brief description of PRUs are given below

2.2.1 PRU Subsystem

The Programmable Real-Time Unit Subsystem and Industrial Communication Subsystem (PRU-ICSS) consists of dual 32-bit RISC cores (Programmable Real-Time Units, or PRUs), shared, data, and instruction memories, internal peripheral modules, and an interrupt controller (INTC). The programmable nature of the PRU, along with its access to pins, events and all SoC resources, provides flexibility in implementing fast real-time responses, specialized data handling operations, custom peripheral interfaces, and in offloading tasks from the other processor cores of the system-on-chip (SoC).

Useful features that we are using and are worth noting are as follow:

- Two PRUs each with:

  - 8KB program memory
  - 8KB data memory
  - High Performance Interface/OCP Master port for accessing external memories
  - Enhanced GPIO (EGPIO) with async capture and serial support
  - Multiplier with optional accumulation (MPY/MAC)

- scratch pad (SPAD) memory with 3 banks of 30, 32-bit registers
- Broadside direct connect between PRU cores within subsystem
- 12 KB general purpose shared memory
- One Interrupt Controller
- One 16550-compatible UART with a dedicated 192-MHz clock.

2.2.2 ADC Subsystem

AM3358 has 200ksps 8 channel muxed single SAR type ADC on it. It is important to understand the functioning of ADC system because we are using few specific features in our implementations (viz Steps, Open Delay and Sample Delay). AM3358 has Touch Screen Controller and Analog to Digital Converter system combined (know as TSC_ADC_Subsystem) [5] . Few main feature of ADC Systems are:

  - Programmable FSM sequencer that supports 16 steps.
  - Software register bit for start of conversion
  - Dual Conversion Modes: One-shot & Continuous
  - Sequence through all input channels based on a mask
  - Programmable OpenDelay before sampling each channel
  - Programmable sampling delay for each channel
  - Programmable averaging of input samples - 16/8/4/2/1
  - Differential or singled ended mode setting for each channel

- Store data in either of two FIFO groups
- Dynamically enable or disable channel inputs during operation

AM3358's ADC system is very flexible and hence bit complicated to use. Each function is controlled by a "step" so each activated feature (either ADC or TSC) is assigned a step number between 1-15 (step -0 is charge step, for touch screen; Step-16 idle) and accordingly the sequencer will iterate through the steps and there by channel(s). sequencer is completely software controlled so the sampling trigger or delay can be configured programmatically.

- **Open Delay & Sample Delay:** User can decide when the voltage should be driven to the ADC and when should ADC start sampling. This delay is used for letting the voltage stabilize in case of weak signal input or impedance mismatch.This is *Open Delay*. Sample Delay decides the width of the SoC width.
- **Averaging of Sample:** ADC system has an averaging system which averages 1(no averaging), 2, 6 ,8 12 and 16 times. If averaging is tunrned ON, say for N samples then ADC system will immediately re-sample the signal (same channel) N times, will average all the samples *and then* will put it to FIFO buffer.
- **Single-Shot or Continuous Mode:** In Oneshot mode sequencer finishes the sampling and conversion of all enabled channels, disables the channels and waits for another trigger. In continuous mode, sequencer loops back to the first step to restart the conversion process all over again, till the STEPENABLE bit is resetted.

2.3 Implementation Overview

An overview of PMU implementation, using AM335x based BeagleBone Black is show in fig

The implementation being described is a synchronized operation of three independent asynchronous subsystems: PRU, ADC and ARM core.

- A C program is written which configures PRU and uploads a binary file in to the PRU(1). PRU binary files does three task:

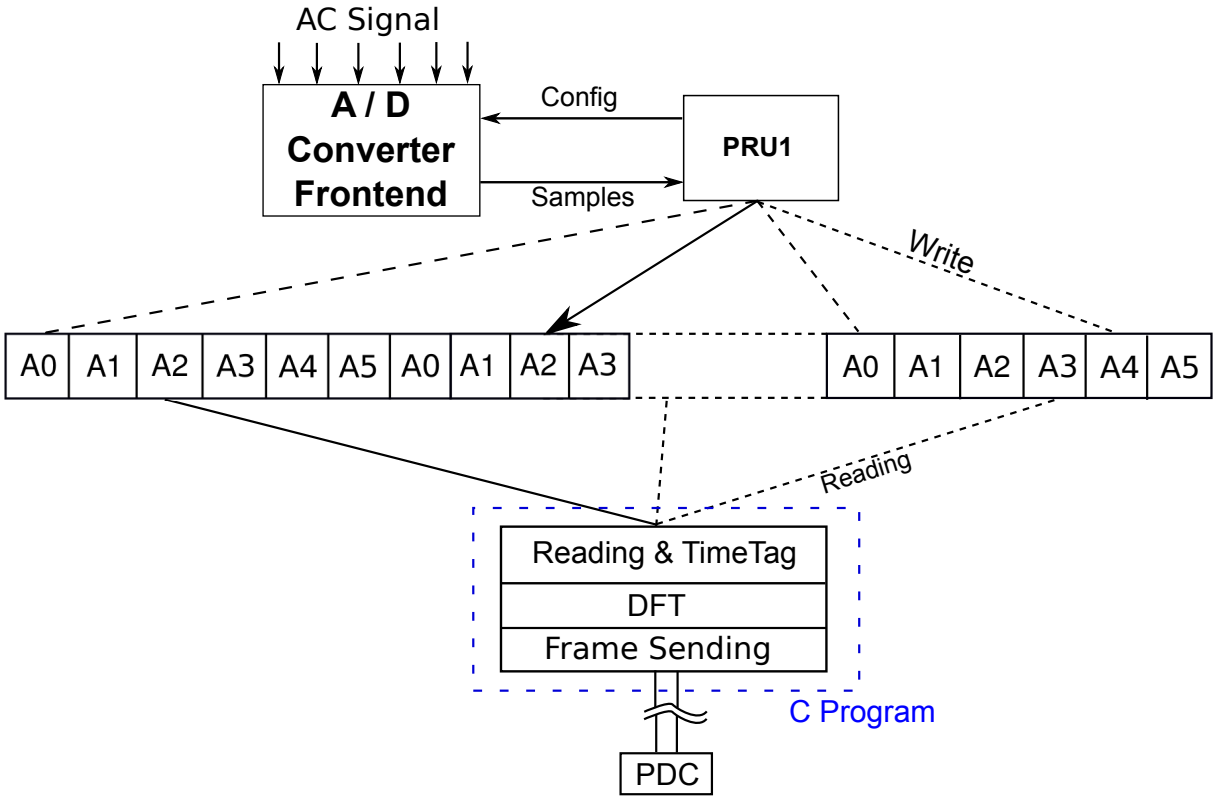

Figure 2.2: Overview of implementation

1. Configure ADC, with
   - Enables 6 channels by writing to `STEPCONFIGx`
   - Configures Open Delay (`OpD`) = 0, by writing zeros to `STEPDELAYx` register
   - Sample delay (`SaD`) = 0
   - Sample Averaging (`SAvg`) = 1 by writting ones to `STEPCONFIGx` registers and
   - Timer delay [`Tmr`]= 156250 ns
   - `Mode` = continuous
2. Define the bank to be used as buffer, and size of buffer
3. Parse the data received from FIFO buffer (of ADC) in to the ring buffer.

- 6 ADC channels are enabled and the sampling rate is set to 128 samples/cycle/channel (using `Tmr` delay). the OpenDelay and Sample Delay are kept zero because our signal strength is enough. Timer delay is configured to $\frac{1}{128*50} = 156250\ ns$.
- In continuous mode the buffer is defined as ring buffer and the buffer length is kept

$128 * 6 = 768 * 2 = 1536$. buffer length is kept double for reading and filling the buffer in Ping-Pong fashion.

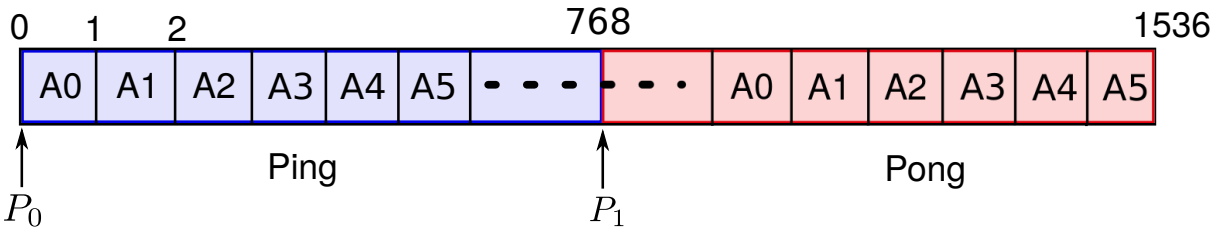

Figure 2.3: Ring Buffer length and Ping Pong depicted

- C program after uploading the bin file, sets the execution bit, This initiates the PRU execution, which signals ADC to start sampling with given configuration. PRU continuously fetches the the data from the output FIFO register of ADC and puts it in to ring buffer *continuously* in sequential order of enabled channels [`A0 A1 A2 A3 A4 A5 A0 A1.....A4, A5`].
- On the ARM side C program creates two pointers and using Ping Pong method over ring buffer reads the ADC samples in chunks. Brief description of how this works is described below and see Fig: 2.4.
  - A buffer of double size then the target size is created (here of 1536 words) and two pointer `P0` and `P1` are created, which points to the start and the middle of the buffer respectively. [Step - 1]
  - Out of two pointer one works as `write head` and other as `read head`. So P0 keeps the track of number of ADC samples parsed in the buffer. [Step-2]
  - When P0 (write head) reaches 768 samples (128* 6, one whole cycle of all channels), pointers are swapped, P1 becomes the write head and P0 becomes the read head and goes to the beginning of the buffer and starts reading, while write head (pointer P1) continuous to write samples into buffer [Step-3]
  - Read operation is faster then write (as PRU has to wait for the samples to arrive depending upon the sampling rate). read head reaches the middle while P1is still writing the samples. [Step-5]
  - After reaching the end of buffer, Pointers are again swapped, P1 again becomes the read head and P0 Write head, which starts reading from the middle and

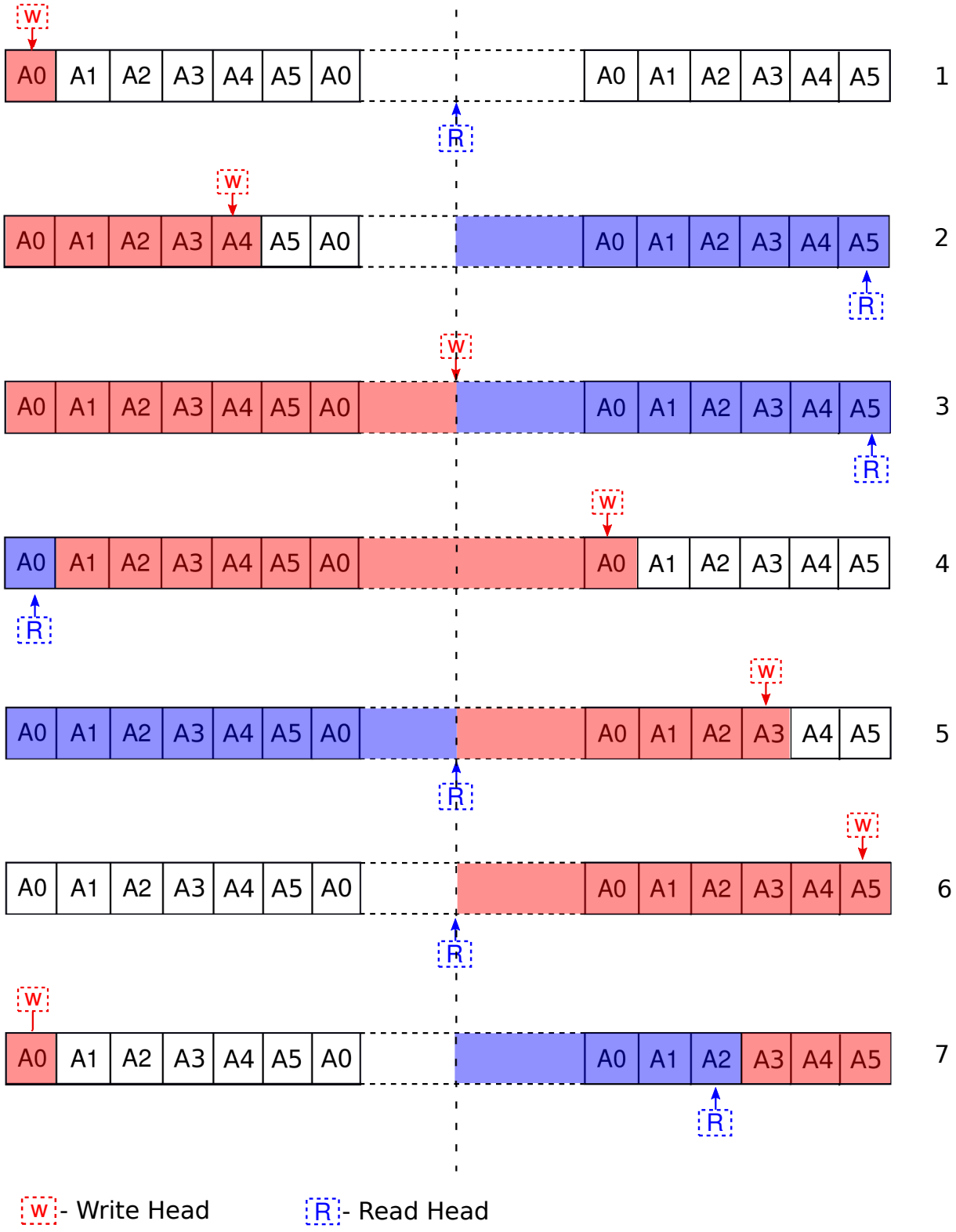

Figure 2.4: Ping-Pong Process Visualized

the write goes to the beginning of the buffer and starts filling the samples. [Step-6]

– From this point it is same as the beginning and the whole cycle repeats. [Step-7]

- This way C program keeps on toggling between two buffers and there by allowing for concurrent reading and writing operation
- A visual depiction of the Ping-Pong process described above is show in the Fig: 2.4

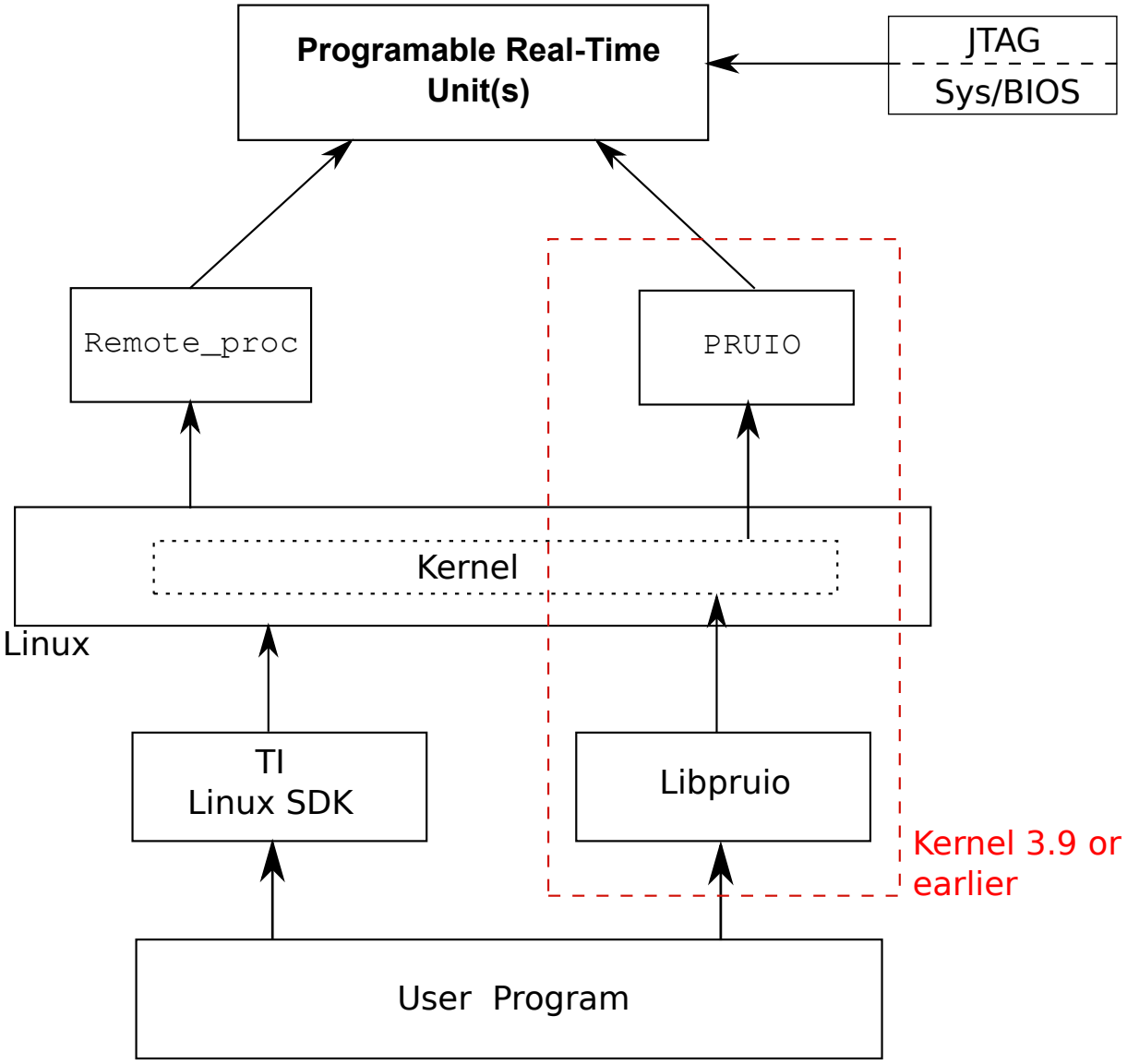

Figure 2.5: PRU Configuration Methods

2.3.1 PRU Configuration

There are several way to configure PRUs, depending upon the kernel version, Operating System and the mode of connection.

1. PRUIO - PASM
2. Remote_Proc
3. Direct firmware loading via JTAG

A visual overview of different way of accessing PRUs is show in Fig: 2.5.

PRUIO

For Kernel version older then 3.9 PRUIO kernel module is used which uses a Device Tree Overlay. Device trees are a way to describe Hardware in system, their memory address, their port number or there function. A good example of it would be how UART is described in the system. Device tree enables addition of new hardware in run-time from User Space, in the kernel architecture.

Usually "Board File" is used in kernel package to describe a hardware of specific embedded system, but given the huge number of ever increasing ARM based devices it was impossible to incorporate all the boards' file in to main Kernel. So Linus Torvalds [6] suggested the use of DT , to simplify the kernel maintenance and up-keeping while providing complete flexibility to describe their processor (something that was already being done by PowerPC manufacturers). So, usage of kernel module and Device Tree enables enables us to configure PRUs and use them. it maps PRU's register memory address to our use space addresses and enables direct access to them.

A separate library called as "libpruio" [7] is used here, for convenience and rapid development. The library provides C and FreeBasic API's for accessing and configuring ADC, GPIO and PWM modules. It uses converts user C code to Assembly Language via PASM and uploads it to the respective PRUs.

Remote_Proc

Modern SoCs have multiple processors and processor cores on them in asymmetric multiprocessing (AMP) configuration. which may be running different instances of operating

system, whether it's Linux or any other flavor of real-time OS . So to enable single kernel to control all those remote processors while abstracting hardware differences and there by reducing the duplication of code *Remote Processor FrameWork* is used [8].

2.3.2 Time Tag and Data Processing

As seen in the previous section, data is read in chunks each chunk has 768 samples which consists of 128 samples from all 6 channels. This makes it more convenient to handle and process the data. Time stamp is stored when the first sample is written to the buffer (for ping) and another time stamp is stored when pointers are swapped (for Pong).

- DFT window of 3 cycle 384 is chosen for better frequency resolution, and then hamming window is applied to smooth out the samples.
- After dot product of samples with hamming constant, DFT is done and frequency is extracted from the beans.
- Frequency resolution is of 0.5 Hz which can seen in figure below.
- After extracting the frequency, Amplitude is extracted by computing the power of all the frequency beans.
- this gives us angle

2.3.3 Communication

After DFT is calculated we have the necessary information to send. Structure of the frame depends upon the configuration and specification of the PMU. Hence as per standards a configuration frames should be communicated by PMU to PDC, which lists following things:

1. Time Format
2. Number of phasors
3. Format of the phasor (rect or polar)
4. Frequency

5. Number of digital status, if any

6. Error Bit

Chapter 3

Results and Discussion

3.1 Chapter 3 Section 1

3.1.1 Subsection 1

3.2 Chapter 3 Section 2

Chapter 4

Chapter 4 Title

4.1 Chapter 4 Section 1

4.1.1 Subsection 1

4.2 Chapter 4 Section 2

Chapter 5

Chapter 5 Title

5.1 Chapter 5 Section 1

5.1.1 Subsection 1

5.2 Chapter 5 Section 2

Appendix A

Appendix 1

Appendix B

Appendix 2

Appendix C

Appendix 3

Appendix D

Appendix 4

Appendix E

Appendix 5

Bibliography

[1] "Circle to sine wave," http://westernau.com/images/Circle-To-Sine-Wave.png.

[2] A. Phadke and J. Thorp, *Synchronized Phasor Measurements and Their Applications*. Springer Science+Business Media, LLC, 2008.

[3] "Phasor measurement unit: History, principal and operation," https://en.wikipedia.org/wiki/Phasor_measurement_unit.

[4] I. P. . E. Society, "Ieee standard for synchrophasor measurements for power systems," 2014.

[5] T. Instruments, "Am335x and amic110 sitaratm processors, technical reference manual," 2011 revised in March 2017.

[6] "Device trees: History, rationale and principal," https://github.com/jadonk/validation-scripts/tree/master/test-capemgr.

[7] "Libpruio: A i/o driver library for beaglebone black," http://users.freebasic-portal.de/tjf/Projekte/libpruio/doc/html/.

[8] "Remote process framework," https://www.kernel.org/doc/Documentation/remoteproc.txt.