ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA073

RF LEAKAGE DETECTOR SYSTEM

M. Jobs, K. Fransson, K. Gajewski, Uppsala University, Uppsala, Sweden

Abstract

FREIA Laboratory is a new facility for developing and testing the instrumentation for particle accelerators. There are two pulsed 400 kW 352 MHz RF sources, presently used for testing the superconducting RF cavities and there is a need to monitor the electromagnetic field in the experimental hall. The RF leakage detector system consists of number of physically identical nodes with one of them configured as a master and the rest as the slaves. Each node supports 3 separate RF measurement channels with a frequency span of 100 kHz to 1 GHz. A desired frequency band is selected using a front-end band-pass filter. The sensitivity of the sensor is -34 dBm and the dynamic range 48 dB. The slaves are battery powered for easy installation. Special care has been taken to minimize the power consumption resulting in battery life to be 0.3 to 1.1 year using 3xAAA batteries in continuous operation. The footprint of the module is 60x100x40 mm. The communication between the master and the slaves uses Wireless Link operating at the 868 MHz ISM band. The system is controlled by EPICS using the StreamDevice driver. The master RF module is connected via RS-232 line and MOXA NPort 5610 server to the control system network.

INTRODUCTION

High power RF sources are used in test laboratories and facilities all over the world as a mean to generate high amplitude, high frequency electromagnetic waves to power different test-setups. The sources are usually based around klystrons, tetrodes or solid-state amplifiers in the kW to MW range. In order to connect the sources rigid coaxial lines or waveguides are typically used and any breaks or disconnections in the RF distribution chain could generate very high ambient fields. In these kinds of environments user safety is of paramount importance since the power levels involved could pose serious risk in case of system malfunction.

In addition to the different interlock stages embedded within the sources and test equipment external measurement devices are also required in order to monitor the working environment for any leakages in the RF-distribution chain which could potentially lead to personnel injuries due to the high power levels in the system.

The RF leakage monitoring and detection system is responsible for continuous measurements of the working environment in order to detect any abnormal ambient levels. In order to provide good coverage of large indoor test-stands such as FREIA [1] the system presented in the paper relies on multiple distributed nodes. It provides good coverage and performance whilst at the same time keeps the overall system cost low. The system is also designed to be able to measure pulsed signals as well as be reconfigurable to cover different frequency bands and to provide multi-band measurements.

SYSTEM ENVIRONMENT

In order to design an RF leakage detection system for an indoor environment it is necessary to have some description of the expected field distribution which has to be measured. Typical high power radio-frequency (RF) test-stands are indoor environments with a high number nearby metallic components like waveguides, metallic cabinets, shielding plates, water pipes and more. These kinds of environments put additional requirements on RF leakage detection system due to the high number of scattering components created when the RF signal propagates from a leak in the system. It is therefore important to predict which power levels of the ambient field will actually be measured when operating the system.

Due to the stochastic behaviour of the field distribution it is best described in terms of its probability density function (PDF). Multi-scattering environments have been well studied over several decades, especially within the mobile communication industry. One of the most common ways of describing the field distribution within a fast fading environment is by modelling it as either Rayleigh of Rician fading. The Rayleigh fading distribution describes the case where all the scattered signals are equal in magnitude whereas the Rician distribution describes the case where one of the signal components is higher in magnitude and dominates. As such the Rician distribution is a more general form of the probability density function of the distributed field and can be describes as [2]:

$$p(x) = \frac{x}{\sigma^2} e^{-(\frac{x^2+A^2}{\sigma^2})} I_0(\frac{Ax}{\sigma^2}) \quad (1)$$

Where σ is the rms amplitude of the scattered signals and A is the rms amplitude of the dominant signal. If the amplitude of the dominant signal is very small compared to the scattered signals the PDF reverts back to that of the Rayleigh distribution. A plot of the expected signal variations can be seen in Fig. 1. This would be the worst operating case in terms of measuring the ambient fields as the variation in the signal level is at its highest. If the dominant signal is much higher than the scattered signals the expected fading variations will be reduced and the ambient signal will experience less variations. In a real world scenario the signal is not expected to suffer quite as deep fading nulls and might be expected to mainly vary in the range of -30 to +6 dB.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA073

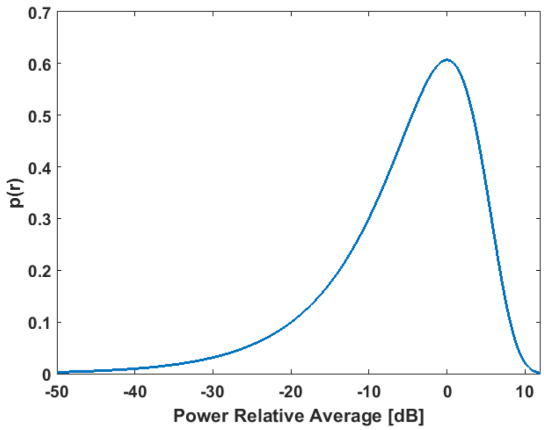

Figure 1: Probability Density Function (PDF) of expected signal variations of the measured signal power.

Safety Guidelines

Depending on which country the installation is operated in the requirements for allowed electromagnetic field exposure might differ. In the setup at FREIA in Uppsala the allowed exposure limits for 352 MHz and 704 MHz, as governed by law, is 10 W/m^2 and 17.6 W/m^2, respectively [3]. The designed system must therefore trigger an alarm close to these limits. However, the exact amplitude of the received signal corresponding to these values will be highly dependent on the design of the pick-up antenna used. As an example, if a normal half wavelength dipole antenna is used at 352 MHz its *Effective Area* (A_{eff}) will have an ideal area of 0.0944 m^2 [4]. This then gives a corresponding received signal level of 29.75 dBm for a 352 MHz with a power density of 10 W/m^2. In the rest of the paper the antenna design itself is not considered and instead focus is put only on giving correct measurements of the input power levels from the antenna input.

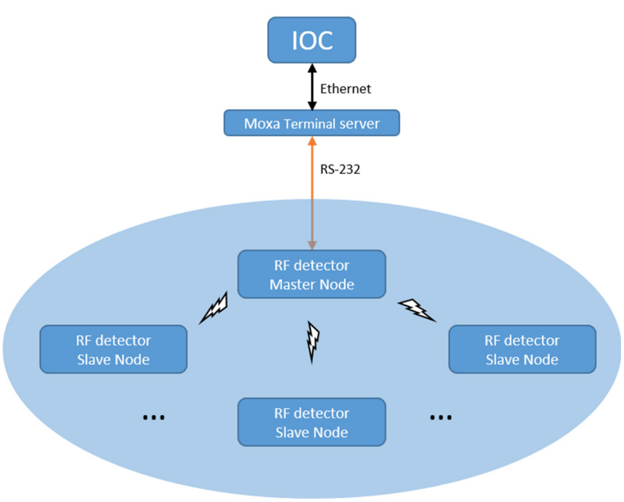

Figure 2: System Topology.

SYSTEM DESIGN

The design methodology used to construct the system was as follows: 1) Specify the base requirements of the system, 2) Specify the key characteristics of the system, 3) Specify the hardware required to fulfil the characteristic requirements and design the base layout, 4) Construct firmware required, 5) Design and implement the interface to Epics. The different design steps are described below.

Topology

In order to provide reliable readings of the ambient field levels the system is designed as a distributed system operating in a star-mesh topology with a single main node (Master) acting as the main hub which collects information from several satellite nodes (Slaves). The Slaves are battery powered and communicate wirelessly with the Master which allows the user to distribute a large number of Slaves freely across the area to get the best possible coverage whilst removing the need of doing additional cabling. The Master node is hardwired to the facility and communicates with the control system over an RS-232 line. This ensured that in the event of any unforeseen issues causing the Slave devices to stop operating there is still at least one main node operating. Identical hardware and firmware package is used for both Master and Slave nodes and differs only in the current configuration of the node. This allows multiple devices to be split and configured into several subsystems if desired.

Specifications

The system is designed to be able to cover a broad range of applications, minimum maintenance whilst at the same time keeping the system cost as low as possible. In order to make maximum use of the possibility to distribute a large number of measurement nodes the cost per device must also facilitate this. The base design criterions for the hardware are as follows:

- Wireless Communication
- 3 RF Receive Channels
- Dynamic Range: -20 to +14 dBm
- Maximum bandwidth: 0.1 to 1000 MHz
- Active Power Consumption: 123 to 515 µA
- Estimated Battery Lifespan: 0.3 to 1.1 year
- Maximum Sample Rate: 2 kHz
- Reliable Range: 100 m
- Acoustic Alarm
- OLED Display
- USB and RS-232 Interface
- 3xAAA Batteries
- USB or 24 V External Power

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA073

Hardware

One of the key design parameters in order to achieve a usable battery-powered wireless system is the minimization of power consumption when operated on batteries. This has been achieved by carefully adapting the component selection and the board schematic in such a way that the system makes maximum usage of sleep periods, peripheral power cycling and firmware efficiency. In normal operating state all interface components such as USB-Interface, OLED display, RS232 etc. are completely disabled. The maximum current consumption when running at 2 kHz sample rate and transmitting measurements to the master at a 1 Hz rate is then 529 µA as seen in Table 1. If not all measurement channels are required the system can be configured for lower power consumption and increased lifespan. *Ex*: running only 1 measurement channel sampled at 500 Hz and a 0.2 Hz data transmission rate would result in an average current consumption of 123 µA. Using an estimated battery capacity of 1200 mAh would then yield an active lifespan of 1.1 years operating 24/7.

Table 1: Design Power Consumption

Component	**Type**	**Avg. Current**
µC	24F16KA102	91-242 µA
Transceiver	MRF89XA	48.6 µA
V-Regulator	MCP1700	1.6 µA
RF-Detector	LTC5507	24-68 µA
Total Current	70% Efficiency	529 µA

The Printed Circuit Board (PCB) was designed for moderate size and low cost. As such the board is designed as a 2-layer board rather than 4-layer with single sided component mounting. This setup lowers the manufacturing and mounting cost of the board. A first generation prototype board under test can be seen in Fig. 3.

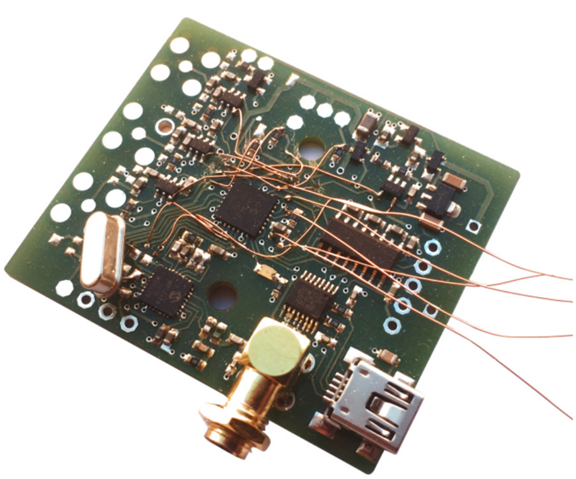

Figure 3: First generation prototype board under test.

Figure 4: First generation operational node. External connector cable seen at left for RS-232 interface and external power. Internal 3xAAA battery holder for wireless operation is provided.

Firmware

The sensor software is written in C and includes OLED display drivers, UART interface, measurement and calibration drivers, custom wireless protocol and the Master/Slave State-Machine. The total memory requirement for the software is 16 kB. The node also uses the internal EEPROM to allow it to store any required user configurations between resets.

The master node is in charge of synchronizing the network and collecting data from the Slave nodes. The Master node also has option to push-out new configurations to the Slaves so that the control system can remotely change measurement parameters such as sampling times, local alarm levels and transmission periods.

When operated as a Slave the device switches to a separate state machine. In Slave configuration the node mainly gathers data and transmits to the Master whilst at the same time keeping track if it is still connected to the network and if there are any updated node configurations pushed out from the master.

In order to provide good quality measurements the raw data measured from the internal RF power detectors has to be linearized across the functional range. This is achieved by storing a measured broadband calibration table for the RF detector in the internal EEPROM of the node which contains measured data in steps of 1 dB across the entire measurement range and measured across several base frequencies between 0.01 to 1.0 GHz. Upon configuration the user selects which frequency to use for each of the individual RF detectors inputs and the system then interpolates the data in the internal calibration table to provide the best possible calibration for the selected frequency.

The node can be configured by means of a serial ASCII command based terminal. The base commands provided allows for read and write operations to be carried out on the nodes data and configuration variables.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA073

Table 2: General Command Format

IOC	Direction	RF master module	Note
W <cmd> <data>	→		
	←	W <cmd> <data>	Normal reply
	←	Invalid Cmd	Command not recognized
	←	Command Failed	Communication with RF slave failed
	←		No reply before timeout
R <cmd> <par>	→		
	←	W <cmd> <par> <data>	Normal reply
	←	Invalid Cmd	Command not recognized
	←	Command Failed	Communication with RF slave failed
	←		No reply before timeout

Integration with Epics

The master mode is connected to an Epics I/O Controller (IOC) via Moxa terminal server model NPort 5610-16. The baud rate of RS-232 serial line is set to 9600. For communication between the IOC and the RF master module a synchronous protocol is used where the IOC sends a query and waits for a reply from the RF module. Topology of the system is shown in Fig. 2.

There are about 30 different commands that are used for configuration, control and data acquisition. The general format of the command is shown in Table 2. The <data> part of the write command (W) and <par> for the read command (R) is empty for some commands. The data sent from the RF module can be in form of a scalar or a waveform. In the latter case specific information is then extracted from the waveforms with help of Epics database logic.

StreamDevice device support [5] is used for realization of the communication protocol. For our system consisting of one master module and three slaves the epics database have about 190 records of which about half is used for interface to the system and the rest is for supporting the database logic.

At FREIA we use Control System Studio (CSS) as an operator's interface (OPI). Examples of the OPI screens are shown in Fig. 5 and Fig. 6.

The average and peak values of the RF field measured by each node are continuously monitored by the CSS's alarm server BEAST. All data is also saved in an archive; at FREIA we use archive appliance [6] as an archiving engine.

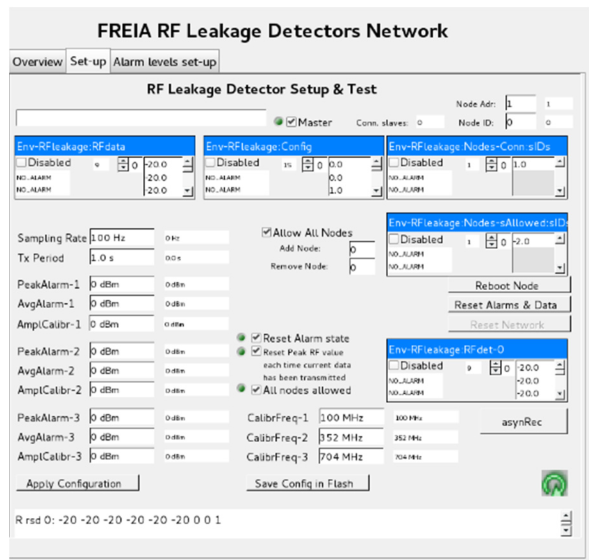

Figure 5: Set-up and debug OPI screen.

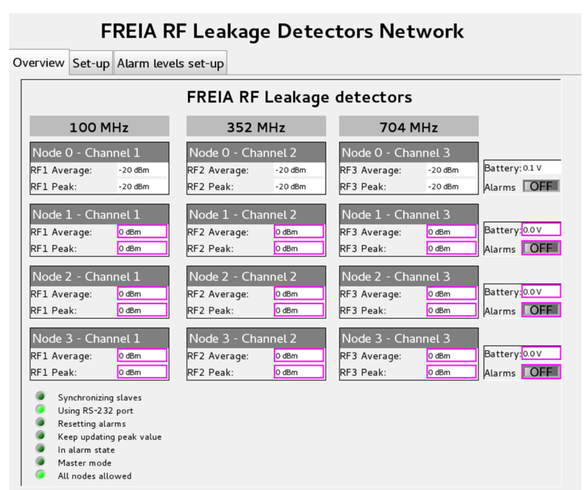

Figure 6: Overview OPI screen.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA073

SYSTEM TEST

The system was tested by mounting a Master node at the test facility and connecting it through the control system interface. A wireless slave was then mounted at an arbitrary location in the facility and connected to an RF signal generator in order to provide a controllable RF power level at the detector antenna input. The input power to the Slave node was then stepped in magnitude in order to evaluate system linearity, accuracy as well as functionality. Both alarm levels and sample rates were updated from the control system in order to verify that the system could successfully push out new configuration to Slave nodes through the wireless network. Measured data was received and stored in the archive. A plot of the measured data can be seen in Fig. 7. The system exhibited good linearity across the measurement range as well as keeping a stable wireless link. The alarm functionality operated as intended with the system going into an alarm state when the input power threshold levels were exceeded on either the Slave or Master side.

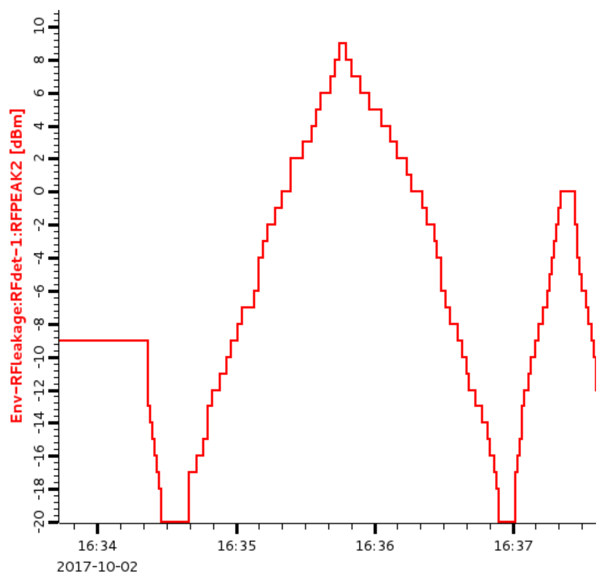

Figure 7: Measured data of power sweep for test received from wireless node and displayed in control system.

CONCLUSION

A distributed RF Leakage Monitoring System has been designed, manufactured and tested on-site at FREIA, Uppsala, Sweden. The system could successfully setup a reconfigurable wireless mesh with multiple sensors and scan for RF leakage over multiple environment locations. The measured data was continuously monitored and stored in the measurement archive at FREIA.

The system exhibited good coverage between the node-to-node communication in the test facility and the wireless Slave nodes could be rearranged easily in order to change the spatial coverage of the monitoring network.

The Epics interface successfully provided the user with options to change multiple parameters such as alarm thresholds, sampling rates and others on both the hard-wired Master node as well as remotely connected Slave nodes.

REFERENCES

[1] M. Jobs *et al.*, "352 MHz Tetrode RF Stations for Superconducting Spoke Cavities", in *Proc. IPAC'17*, Copenhagen, Denmark, 2017, paper THPIK090, http://dx.doi.org/10.18429/JACoW-IPAC2017-THPIK090

[2] T. S. Rappaport, "Wireless Communications: Principles and Practice", 2nd Edition, 2002, ISBN: 0130422320.

[3] "Elektromagnetiska Fält", The Swedish Work Environment Authority, AFS 2016:3, Appendix 8.

[4] C. A. Balanis, "Antenna Theory: Analysis and Design", Third Edition, Eq. 4-92, ISBN: 047166782X.

[5] Epics, http://epics.web.psi.ch/software/streamdevice

[6] Epics Archiver, https://slacmshankar.github.io/epicsarchiver_docs/.