A Prototype of Wireless Power and Data Acquisition System for Large Detectors

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Abstract

We have developed a prototype detector and data acquisition module that incorporates wireless power and wireless data transmission techniques. The module has no electrical connections. It receives power using photovoltaic devices, and communicates control, timing, trigger, and data using the 802.11n wireless communication standard. The work is part of a study for building a large detector having many readout channels, where it is desirable to reduce the cable plant and infrastructure. The system could also be deployed in smaller detectors that require mobility or are difficult to cable due to extreme conditions. We describe the design and operation of the prototype module, including benchmark performance measurements, and discuss aspect and issues in extrapolating to a large detector system.

Keywords: Wireless communications, RF, Optical

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1. Introduction

The goal of this R&D project was to design and build a detector module that operates from wireless power and transmits data using wireless data transmission techniques. The motivation is the elimination of the massive cable plants that are typical of large detectors, thereby reducing detector dead mass, simplifying installation and repair, and possibly reducing cost. In particular, cabling can create technical challenges for detectors in remote locations or hostile environments. We used this work to study the feasibility of building a large detector that would be constructed as an array of single detector modules. The technologies that we used in this work are not necessarily optimal for all detectors and experiments. Rather, our goal was to choose technologies that could demonstrate the concept as a basis for thinking about the challenges and issues in building a large detector using these techniques. One of the motivations in this work was consideration of building a read-out system for a large neutrino detector such as a water-Cherenkov detector configured with photomultiplier tubes (PMT). The readout rate of these detectors is often dominated by the dark noise rate, which can be of order 10 KHz [1]. Examples of such detectors include water-based LBNE [2], MEMPHYS [3], Hyper-K [4], and CHIPS [5] detectors. Detectors used for homeland security also use similar technologies and techniques. Simplifying the implementation of large detectors with high channel counts could facilitate detection of nuclear materials and other contra-band.

Other applications could benefit from infrastructure simplification, increased mobility, and stand-off distance capability of wireless techniques. Some examples of these include monitoring of the neutrino flux at a nuclear

26 reactor, large mobile neutron detectors for detection of radioactive material
27 in security applications, and detectors operating in high-radiation areas. Op-
28 eration in real world conditions sometimes requires the ability for detectors
29 to be mobile, and/or the ability to operate continuously for long periods of
30 time, both of which can benefit from using low-power wireless techniques.

31 For neutrino and other low-rate experiments, the single photoelectron
32 rate often dominates the event rate. If we assume for each event that the
33 data would be comprised of 6 bytes, 2 bytes of pulse height information
34 and a 4 byte time-stamp, at 10 kHz, this translates to 60 kBytes (kB), or
35 480 kbits/second (kb/s). For a single detector element, these data rates
36 are achievable with a wireless readout. Extrapolating to a detector with a
37 large number of channels (for example, 40000 PMTs are considered in some
38 variations of a water-based LBNE [2]) translates into a data rate (on the
39 order of ~ 20 Gb/s in the LBNE example), which is one of the challenges for
40 the wireless readout.

41 Successful demonstration of an all wireless system could be transforma-
42 tional when realized in a practical, cost effective, and reliable fashion. We
43 intend to use this prototyping work as a starting point for using these prin-
44 ciples in new read-out technologies.

45 **2. Design Considerations**

46 For wireless data transmission, we considered two techniques: radio-
47 frequency (RF) wireless and free-space optical data transfer. These will be
48 discussed in more details. For the wireless power transfer, we considered
49 RF and optical methods. There are other approaches for transmitting the

Table 1: Target specifications for the wireless data acquisition system.

Specification	Target
Maximum event rate (single p.e.)	10 kHz
Bytes per event	6 (2 pulse height, 4 time-stamp)
Average data rate per front-end channel	60 kB/s
Total power consumption @ 10 kHz	250 mW
Digital	120 mW
Front-end	30 mW
HV	100 mW
Data transfer rate	35 Mb/s
Bit error rate	$< 1 \times 10^{-12}$
Additional Features	Self-trigger for pedestals Data pull Programmable HV Programmable Discriminator

50 power wirelessly such as strongly coupled magnetic resonance techniques [6].
 51 Wireless technologies have been studied for a wide variety of applications; for
 52 example in space and radiation research [7], radioactive material sensor net-
 53 work [8] and in the field of radiation detection [9]. In selecting technologies,
 54 a preference was placed on the use of inexpensive, off-the-shelf technologies
 55 that could be implemented relatively easily, with minimal risk, and which
 56 could meet the performance goals of this project. The initial target specifi-
 57 cations for the prototype system are summarized in Table 1. The parameters
 58 can generally be obtained using off-the-shelf solutions. Our estimates using

existing hardware [10, 11, 12, 13, 14] are ~ 100 mW for the high-voltage generation of the PMT, ~ 120 mW for the data processing and wireless data transmission, and ~ 30 mW for the front-end needed for processing and digitization of the PMT signal.

2.1. *Wireless Data Transmission*

For wireless data transmission, optical links generally support higher data rates compared with RF. Individual free space links over distances of meters can achieve transfer rates of approximately 1 Gb/s [15]. However, RF transmission does not require line-of-sight, and an individual transmitter can communicate with many front-end receivers. RF data transmission was chosen for this project for these reasons. An issue with RF is that the bandwidth of an individual link is typically modest, approximately 100 MB/s, and the available RF bandwidth is shared by all transmitting elements of the detector.

There are two primary categories of commercial wireless data technologies: mobile/cellular [16] and wireless local area network (WLAN) [10]. We found that cellular networks, including the latest 4G technologies, offer higher distance ranges than WLAN technologies, but this comes at the expense of a lower overall data rate [17]. For this project, we focused on WLAN technologies, since they have the highest data throughput, which is the rate of successful message delivery over a given communication channel. We selected the 802.11n protocol, which at the time, offered the highest data throughput of 65 Mb/s [11]. The available payload data rate, which is the maximum available data throughput after accounting for the error correction overhead is ~ 35 Mb/s. This was sufficient for our single prototype front-end.

84 The 802.11n wireless network operates in both the 2.4 GHz and 5 GHz
 85 frequency bands. We utilized the 5 GHz band in our study, which has an
 86 overall bandwidth of approximately 1.2 GHz from about 4.9 GHz to 6.1 GHz.
 87 This ignores limitations imposed by the governing agencies that dictate the
 88 use of the electromagnetic spectrum. Under certain circumstances, the full
 89 spectrum can be available for use with devices capable of dynamic frequency
 90 selection [12]. The approach is needed in order to implement the use of a
 91 large number of access points in a large detector system to accommodate
 92 the total payload data rate needed by the data acquisition system. Single
 93 stream 802.11n access points can have an individual operating bandwidth of
 94 20 MHz or 40 MHz. With 20 MHz wide channels, it should be possible to
 95 populate the 1.2 GHz wide frequency band with up to 48 access points. For
 96 a single stream 802.11n link this translates into a total payload data rate of
 97 1.68 Gb/s, as illustrated in Fig. 1. The system consists of many access points
 98 (~ 48) each communicating to many clients (~ 64), for a total of 3072 clients.
 99 This assumes 480 kb/s per front-end and a transfer rate of 35 Mb/s.

100 For the detectors with a large number of channels, the available payload
 101 data rate is insufficient. There are two potential extensions of this concept
 102 that might result in an increased data throughput. The first is the use of
 103 directional antennas and intrinsic shielding created by the detector volume to
 104 allow the same frequency range to be re-used in different locations on the de-
 105 tector. The second approach is to include extensions of the standard 802.11n
 106 protocol that allow for multiple-input and multiple-output (MIMO) [13] wire-
 107 less streams, which could significantly increase data throughput. For exam-
 108 ple, 4×4 MIMO requires 40 MHz wide channels, which means the 1.2 GHz

Figure 1: Allocation of frequency space for wireless data transmission.

frequency band would support approximately 24 access points. The 4×4 MIMO implementation would then support 4 simultaneous transmit and receive streams to yield a data throughput of 600 Mb/s, which translates into a maximum payload data rate of 320 Mb/s. The total “sector” payload data rate would then be 7.68 Gb/s.

The combination of these two extensions to the multi-access point configuration could provide much higher data throughput to read-out a detector with large channel count. Note that the above estimates do not account for latency in the communication. In practice, the latencies will impact the achievable throughput. In a real system, the DAQ system would probably have to “pull” data from the front-ends. This requires a handshake between client and access point and increases latencies slightly. However, this controls the readout process and avoids the need for clients requesting to send data.

122 For example, the server might request data from each front-ends once per
123 second, provided that there is adequate data storage in the front-ends, and
124 that the event rates are modest.

125 2.2. *Wireless Power Transmission*

126 We considered and tested both optical and RF power transfer methods.
127 The optical demonstrator utilizes a high-power light-emitting diode (LED)
128 that was collimated into an 8 inch diameter beam. The light was received
129 by a photovoltaic (PV) panel, as shown in Fig. 2. We used an OSRAM SFH
130 4751 LED with 3.5 W optical output. The LED wavelength is 940 nm, which
131 matches the peak efficiency of the Delsolar $156 \times 156 \text{ mm}^2$ photovoltaic cell
132 used in our $312 \times 280 \text{ mm}^2$ PV panel array. Figure 3 shows the power received
133 from this system as function of transmission distance. The performance
134 met our prototype requirements of receiving 0.25 W power at 5 meters. In
135 addition to the studies conducted in our lab, we also performed a test with the
136 solar panel array exposed to the sun light. We found that it was possible to
137 receive more than 0.25 W to the prototype front-end, under bright conditions.

138

139 The RF power transfer test consisted of a function generator driving a
140 14 dBi gain Yagi antenna at 915 MHz with an output power of 10 dBm.
141 The receiver used an 11 dBi gain patch antenna, as shown in Fig. 4. The
142 measurements were taken inside a large room, and the apparatus was placed
143 at ~ 2 m from the floor to reduce the scattering from surrounding objects.
144 The data from these tests, as a function of transmission distance, are shown
145 in Fig. 5. The data points are in good agreement with the expectation from
146 the Friis transmission equation [18], which relates the ratio of power received

Figure 2: Apparatus for optical power transmission. The photovoltaic receiver (left), the LED and lens are inside a tube (right).

Figure 3: Power received (mW) by the photovoltaic panel as a function of distance (m) from the optical source. The optical source used was a 3.5 W LED with a 940 nm wavelength and a focusing lens.

147 P_r to power transmitted P_t for a given pair of antennas with gains G_t and
 148 G_r , operating at an wavelength λ , and separated by a distance R , as given in
 149 Eq. 1. There is a rapid fall off of received power as the transmission distance
 150 increases. At 5 meters the power loss is 20 dBm, which requires a 25 W
 151 source to receive 250 mW, our target power.

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \quad (1)$$

For our prototype device, the optical system was the chosen approach. The

Figure 4: Apparatus for RF power transmission. The RF transmitter (14 dBi gain Yagi antenna) with a function generator is in the right, the RF receiver (11 dBi gain patch antenna) with a oscilloscope is in the left.

152

153 power source and receiver were relatively easy to implement. RF power trans-
 154 mission requires converting the RF power into a DC supply, which is com-
 155 mercially available but typically limited to ~ 100 mW of received power [14].
 156 The optical power transfer technique met the power requirements for this
 157 demonstrator. RF power could be a practical choice for a large detector,

Figure 5: Power loss (dB) in the RF power transmission test as a function of distance (m) from the source. Solid dots with error bars are the measurements and open dots are the expectation from the Friis transmission equation. The source is a 915 MHz 10 dBm transmitted through a 14 dBi gain Yagi antenna and received by an 11 dBi gain patch antenna. The scale on the right shows the power that would be received for a 25 W (44 dBm) source.

158 since one source can power many transmitters. This could potentially reduce
159 the complexity and cost of the system. For example, at 5 meters the same
160 power ± 3 dBm is being transmitted into a 2×2 m² area. For a 50 W output,
161 a single equivalent source could power as many as 40 front-ends depending on
162 the packing density. One potential issue to be addressed in a future studies
163 when using the RF power transfer techniques is electromagnetic interference
164 from the RF signal.

3. Description of the Prototype System

The prototype readout system that we designed and built for this demonstration is shown in Fig. 6. It consists of a laptop computer running Scientific Linux [19]. A data acquisition program was written to receive and store the incoming User Datagram Protocol (UDP) [20] packets. For each asynchronous PMT trigger, the pulse height and time-stamp are stored. The front-end transmits the data as a single UDP packet to the server once per second. The program running on the server receives and stores the UDP packets. Currently only “data push” from the front-end is implemented. As mentioned in section 2, implementing “data pull” would be preferred to improve the throughput from multiple front-ends in a large detector.

Figure 6: Configuration of the prototype readout system. The front-end (left) transmits data wirelessly and collected by the access point (upper right) and stored in PC with scientific linux (lower right).

176 3.1. Hardware Description

177 Figure 7 shows a block diagram of the wireless demonstrator. The pro-
 178 totype system is comprised of 4 boards that include: a board for generating
 179 high voltage for the PMT; a front-end board for shaping and digitization of
 180 the PMT signal; a digital board for processing the data and wireless data
 181 transmission; and a power board for receiving wireless power and generating
 182 the different voltages needed by the system. The system was designed to
 183 connect to a photovoltaic panel and send data wirelessly using 802.11n in
 184 the 5 GHz band. The four boards in the PMT base are shown in Fig. 8
 (left), and the complete system with PMT is shown in Fig. 8 (right).

Figure 7: Block diagram of the wireless prototype system.

185

186 The power board uses a LTC 3105 [21] switch mode step-up converter
 187 to convert the 1.85 V received from the photovoltaic panel into 5 V, which

Figure 8: Left: Four printed circuit boards of the wireless prototype system assembled within the PMT base. The boards are power board, digital board, front-end board, and the high-voltage board. Right: Picture of the completed system shown with light tight PMT enclosure and photovoltaic panel attached to PMT base.

188 is used as the system voltage. The energy is stored in a series of ultra-
 189 capacitors [22] with an effective total capacitance of 2.5 F. We used step-
 190 down convertors [23] and step-up converters [24] to convert 5 V into voltages
 191 needed to run the system components.

192 The digital board hosts the processor, wireless radio, and additional digi-
 193 tal integrated circuitry (i.e. external low-power Static Random-Access Mem-
 194 ory (SRAM) and Serial Peripheral Interface (SPI) flash [25]). The wireless
 195 radio used was a cBOWL221a [11] commercial board. It uses 802.11n single
 196 stream communication and has an SPI interface. This module was cho-
 197 sen because of its low power consumption. The radio incorporates all of
 198 the 802.11n protocol, with the Transmission Control Protocol (TCP)/IP or
 199 UDP/IP stack incorporated inside the processor. The processor used was a
 200 Microsemi A2F200 Smart Fusion [26]. The Field Programmable Gate Array
 201 (FPGA) fabric is used for the discriminator logic, Analog-to-Digital Con-
 202 verter (ADC) readout, time-stamping, and event word generation. It directly
 203 accesses the external memory and stores the events using the same memory

204 controller as used by the processor.

205 The high voltage board uses a Cockroft-Walton (CW) switching circuit to
206 boost the 24 V input voltage up to 2000 V. This also operates from wireless
207 power, and the noise performance was sufficient to measure single photo-
208 electrons.

209 The front-end board includes a charge-sensitive preamplifier, shaping am-
210 plifier, programmable discriminators, and a 12-bit ADC. The output of the
211 charge sensitive amplifier connects to both a uni-polar and a bi- polar shaping
212 amplifier. The uni-polar shaping amplifier output is digitized by an AD7451
213 ADC [27] for measuring the pulse-height. The bi-polar shaping amplifier is
214 used as the input to a pair of comparators, one of which is used for pulse-
215 height discrimination and the other for timing. The comparator outputs
216 connect to the A2F200 FPGA fabric (digital board) over the data and con-
217 trol bus. As mentioned earlier, the A2F200 FPGA fabric is used for the
218 discriminator logic to control the ADC readout.

219 *3.2. Performance Discussion*

220 The prototype system has been built and tested. It was powered wire-
221 lessly using the optical source, which was received by the photovoltaic panel.
222 Tests were performed with the system running from wireless power and by
223 sending and receiving the data wirelessly. The performance achieved is sum-
224 marized in Table 2.

225 As shown in the Table 2, the power consumption of the system is 386
226 mW, higher than the initial 250 mW target. The primary reasons for the
227 increase are higher power consumption in the digital and the high-voltage
228 boards. In the case of the digital board, the target specification was based

Table 2: Summary of initial goals and achieved performance for the wireless data acquisition system.

Specification	Target	Performance
Total power consumption (@ 10 kHz)	250 mW	386 mW
Digital	120 mW	216 mW
Front-end	30 mW	39 mW
HV	100 mW	131 mW
Maximum event rate	10 kHz	80 kHz
Data transfer rate	35 Mb/s	11 Mb/s
Bit Error Rate	$< 1 \times 10^{-12}$	Dropped Packets

on Microsemi spreadsheet power estimator, which appears to underestimate actual operation. The high-voltage board used a resistive divider in the PMT, rather than direct connection of dynodes to the CW supply. This caused the power consumption to increase. We believe that the original power consumption goal can be achieved given that both of these problems are understood, although noise from the CW coupling into the dynodes would have to be addressed.

The system is capable of sending greater than 10k events/s (60 kB/s). However, the critical parameter for performance in a large detector is the maximum data transfer rate. The specification of 35 Mb/s is the maximum transfer rate of an 802.11n single stream link, and this was our target. While this is achievable with the radio used here, it does necessitate zero SPI bus latency and a 50 MHz SPI clock. The maximum transfer rate that we achieved was 11 Mb/s. The reason for this was twofold. First, the maximum

243 SPI clock rate in the A2F200 is set by the master clock divided by 4. This
244 limits the maximum SPI clock rate to 25 MHz. Second, latencies caused
245 by FreeRTOS [28], the driver code, and the speed of the A2F200 processor,
246 account for the remaining difference. The pin-compatible A2F500 supports a
247 50 MHz SPI clock and will be implemented in the future. This simple change
248 should yield 18 Mb/s. Reducing the latency would require the elimination
249 of FreeRTOS and driver optimization.

250 Our target bit error rate (BER) was less than 1×10^{-12} . A bit error
251 rate test (BERT) program was written to analyze the performance. The
252 prototype system was run continuously over 100 hours with no bit errors
253 observed in any received packets. This is a result of operation of a relatively
254 simple system with one broadcast source at a time, in the largely unused
255 5 GHz band in our lab. It is also due to the forward error correction that
256 is incorporated in the 802.11n protocol. However, significant numbers of
257 dropped packets were observed, on the order of 1 in 2000. It is believed that
258 this is due to the use of UDP. While more efficient than TCP, UDP does
259 not have retransmission capabilities. We traced the problem to our access
260 point, having observed the drop packets with the same frequency by using
261 a computer to generate fake data. The nature of UDP will require some
262 consideration of error detection and recovery for a large system. It may be
263 possible to significantly reduce the systematic packet loss by using a protocol
264 such as the Pretty Good Protocol (PGP) [29], for dropped-packet detection
265 and retransmission mechanism.

266 A few results of data collected with the prototype system operated from
267 wireless power and with wireless data readout are shown in Fig. 9. The

Figure 9: Upper Left: Measurement of pedestal. The system is operated with conditions 10k events/s, self-triggered, HV turned on with no PMT, system powered wirelessly and wireless readout. Upper Right: Response from electronic charge injection. The system is operated with conditions self-triggered, PMT HV on, system powered wirelessly and wireless readout. Lower Left: Response from 60 keV ^{241}Am source. The system is operated with conditions 1k events/s, self-triggered, PMT HV 1300V, system powered wirelessly and wireless readout. Lower Right: Response from 661.7 keV ^{137}Cs source. The system is operated with conditions 250 events/s, self-triggered, PMT HV 1200V, system powered wirelessly and wireless readout.

front-end circuit exhibits very low noise as demonstrated with the pedestal
 data. The integral linearity over the full digitization range shown in Fig. 9
 (upper right) is better than 0.4%. To test remote data acquisition capability,
 a sodium iodide crystal was attached to the PMT and tested with ^{241}Am

272 (Fig. 9, lower left) and ^{137}Cs (Fig. 9, lower right) sources.

273 4. Summary and Future Prospects

274 We successfully designed and built a wireless data acquisition system
275 implemented in a photomultiplier tube base that operates from wireless power
276 and sends data wirelessly. The power consumption, while slightly greater
277 than our target, is still low enough to allow the system to operate from our
278 optical power transfer system. Future improvements would include improving
279 the SPI clock rate by using the A2F500, eliminating FreeRTOS, and reducing
280 the SPI bus latency. This will reduce power consumption in the digital board.
281 The high-voltage board should be redesigned to integrate correctly into the
282 chosen PMT. In the longer-term, RF power transfer should be explored to
283 facilitate the simplification of using one transmitter to power many receivers.
284 Investigating the use of a custom application-specific integrated circuits for
285 low-power operation of the front-end and Cockroft-Walton control circuitry
286 might also be considered for a larger system.

287 The use of the pin-compatible A2F500 SmartFusion device should in-
288 crease the transfer rate from 11 Mb/s to 18 Mb/s. Assuming 480 Kb/s
289 average data rate from our front-ends and assuming a conservative estimate
290 of the latency between request for data and transmission of data of 10 ms,
291 the burst transfer rate achieved would support 18 and 27 front-ends for 11
292 and 18 Mb/s respectively. A system with 48 access points would support
293 1296 front-ends.

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