INL/EXT-21- 54866
Revision 1

Enabling Predictive Maintenance with Wireless Instrumentation in Balance of Plant Systems

M3CA-18-ID-IN__-0703-013

Vivek Agarwal

July 2019

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-21- 54866
Revision 0

Enabling Predictive Maintenance with Wireless Instrumentation in Balance of Plant Systems

Vivek Agarwal

July 2019

Idaho National Laboratory
Idaho Falls, Idaho 83415
http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-NE0008255

(This page intentionally left blank)

ABSTRACT

One of the major contributors to the total operating costs of domestic nuclear fleet of reactors today is the operation and maintenance (O&M) costs. These include labor-intense preventive maintenance programs involving manually-performed inspection, calibration, testing, and maintenance of plant assets at periodic frequency and time-based replacement of assets at periodic frequency, irrespective of their conditions. This has resulted in a *labor-centric business model to achieve high capacity factors*. To build an optimal maintenance program, it's time to transition from this labor-centric business model to a *technology-centric business model*. Fortunately, there are technologies (advanced sensor, data analytics, and risk assessment methodologies) that will support this transition. The technology-centric business model will result in significant plant life extension and reduction of time-based maintenance activities. This will drive down O&M costs as labor is a rising cost and technology is a declining cost. This approach will lay the foundation for real-time condition assessment of plant assets, allowing condition-based maintenance to enhance plant safety, reliability, and economics of operation.

The goal of this project is to address challenges in the area of digital monitoring, i.e., the application of advanced sensor technologies (particularly wireless sensor technologies) and science-based data analytic capabilities to advance online monitoring and predictive maintenance in nuclear plants to improve plant performance (efficiency gain and economic competitiveness). To achieve the project goal, in partnership with Exelon Generating Company (Exelon), researchers from Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) are performing research and development (R&D) to demonstrate application of wireless sensors using the distributed antenna system and advanced data analytics to achieve predictive maintenance.

In the report, we describe the plant system identified for achieving predictive maintenance along with the current level of instrumentation. The plant system identified is a condensate and feedwater system. The current level of instrumentation on the condensate and feedwater system provides the data collected by the partnering nuclear plant owner. Some of the data are collected as part of plant processes on a continuous basis, while some data are collected periodically as part of preventive maintenance strategy. Based on the range of data values, a data completeness evaluation will be performed to identify a gap in the data and recommendations will be made to install additional sensor modality to bridge the gap.

ACKNOWLEDGMENTS

This report was made possible through funding by the U.S. Department of Energy Nuclear Energy Enabling Technologies Program. We are grateful to Suibel Schuppner at the U.S. Department of Energy and Craig Primer at Idaho National Laboratory for championing this effort. We thank Katie Stokes for technical editing and formatting of the document.

(This page intentionally left blank)

CONTENTS

FIGURES

TABLES

(This page intentionally left blank)

ACRONYMS

BOP	balance of plant
BS	Base Station
DAS	Distributed Antenna Systems
eNB	ENodeB
FW	feedwater
LTE	Long Term Evolution
MRDU	Mid-Power Remote Drive Units
MROU	Mid-Power Remote Optic Unit
MS	Mobile Station
O&M	Operations & Maintenance
OLM	online monitoring
PM	Preventive Maintenance
RF	Radio Frequency
RFP	Reactor Feedwater Pump

(This page intentionally left blank)

Enabling Predictive Maintenance with Wireless Instrumentation in Balance of Plant Systems

1. INTRODUCTION

The goal of this project is to address an unsolved challenge in the area of digital monitoring, i.e., the application of advanced sensor technologies (particularly wireless sensor technologies) and science-based data analytic capabilities to advance online monitoring (OLM) and predictive maintenance in nuclear plants and improve plant performance (efficiency gain and economic competitiveness). To achieve the project goals, specific project objectives (as presented below) will be completed during the period of performance of the project.

1) Design a general methodology for techno-economic analysis of wireless sensor modalities for use in monitoring equipment condition, especially in balance of plant (BOP) systems in a nuclear power plant
2) Apply data science-based techniques for decision making and discovery, to develop and evaluate integrative algorithms for diagnostic and prognostic estimates of equipment condition using of structured and unstructured heterogeneous data distributed across space and time (i.e., analytics-at-scale), including new data from wireless sensors in a nuclear plant
3) Develop a visualization algorithm to present the right information to the right person in the right format at the right time
4) Validate the developed approaches and algorithms using independent data from an operating plant.

One of the objectives includes identification of a BOP asset or system in collaboration with Exelon Generation Company (Exelon) that could be used as a target asset to install wireless sensors to enhance OLM and to develop a predictive maintenance strategy.

To support the installation of wireless sensors on plant assets, Exelon are building their wireless architecture by utilizing the distributed antenna system (DAS). Idaho National Laboratory proposed wireless network deployment strategy for a nuclear power plant [1] that would enable application from low power to high power, low-frequency range to high-frequency range, and short-range to long-range communication, as shown in Figure 1. The whole network topology is predominantly operated using DAS Long-Term Evolution (LTE) system or wireless local area network system since they can enable:

- High bandwidth and data transmission rate with low latency
- Prioritized data transmission based on the required Quality of Experience or Quality of Service
- Most of the wireless technologies can have either a Wi-Fi or a DAS system as their back-end networks (e.g. a Bluetooth Device can connect to Wi-Fi in the back end to upload its data to the internet)
- LTE or Wi-Fi are the two technologies that can act as bridges between end devices/other wireless technologies and the internet, or an outside network
- Easy network maintenance by bringing all the networking technologies under one network architecture.

The transition to predictive maintenance will improve plant economics by reducing costs associated with operating and maintaining the current domestic fleet of nuclear plants (i.e., 97 operating units). Continuing to operate nuclear plants in an electricity market selling wholesale electricity for $22/MWh (PJM spot price, July 2018) becomes unsustainable with the current maintenance paradigm. The average cost to produce electricity in the nuclear industry is approximately $34/MWh, with $22/MWh attributed to operations and maintenance (O&M) costs. On average annual O&M costs equate to approximately $145M per station.

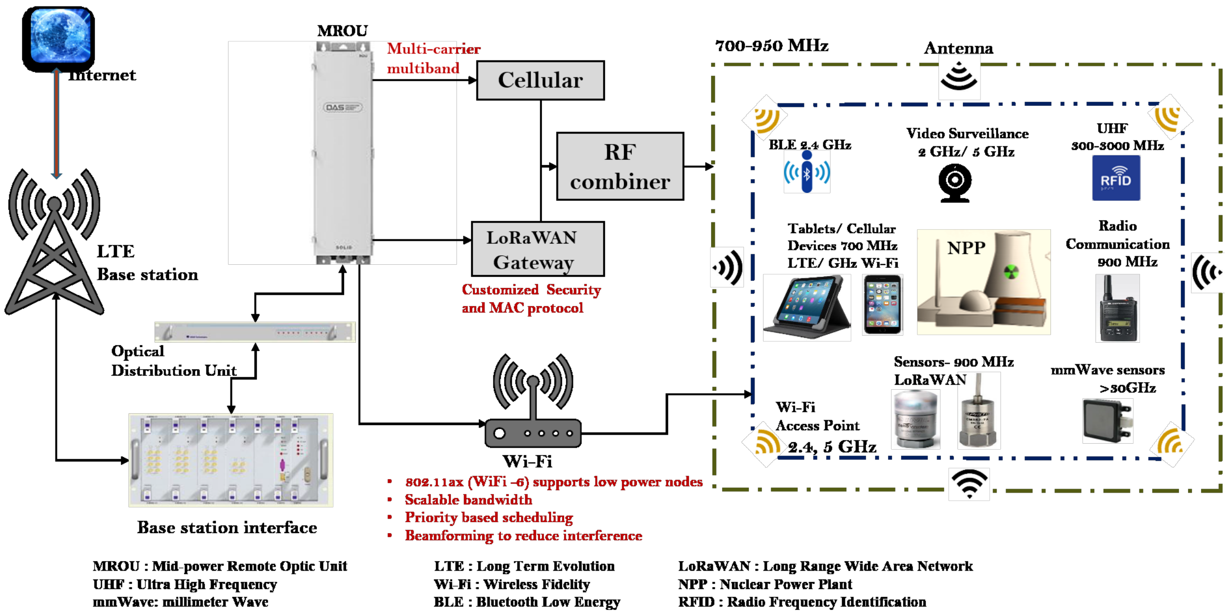

Figure 1. Envisioned multiband wireless technology for nuclear power plant automation**.**

One major contributor to total operating costs in domestic nuclear power plants today is O&M costs, which include labor-intense time-based preventive maintenance (PM) programs. PM programs involve periodic manually-performed inspection, calibration, testing, and maintenance of plant assets at periodic frequency and time-based replacement of assets, irrespective of their conditions. This has resulted in a labor-centric business model. It is time to transition from this labor-centric business model to a more optimal predictive maintenance program. To enable this transition, a reliable method is needed to assess equipment condition and risk of failure. Fortunately, there are technologies (advanced sensors, data analytics, and risk assessment methodologies) that can enable this transition. The technology-centric business model will result in significant cost savings by reducing costly PM activities.

The projects tasks, significant results, discussions, and conclusions are summarized in remainder of this report, which is organized as follows:

- Section 2 discusses the Condensate and Feedwater System.
- Section 3 discusses the wireless DAS architecture to support wireless sensor installation at a Exelon plant site.
- Section 4 presents a summary and discussion of a potential path forward.

2. CONDENSATE AND FEEDWATER SYSTEM

Exelon, in partnership with INL, identified condensate and feedwater system as the BOP system studied in this research. Exelon provided INL with the list of existing instrumentations on the condensate and feedwater system across the fleet. These instrumentations provide different measurements on the identified BOP system which includes temperature, pressure, flowrate, vibration, speed, gross load, and hours of operation. Exelon’s sensitive information related to condensate and feedwater system is not presented in this report. The information shared is very useful in performing a data completeness evaluation to understand if any additional measurements are required to support predictive maintenance. If additional measurements are required, what would be the sensor modality that needs to be installed and connected to plant process computer.

A general description of the elements of condensate and feedwater systems adopted from [2] are presented in this section without specifying any plant information.

The condensate and feedwater system prepares water for use in reactor systems and circulates the water from the main condenser to the steam generator (in the case of a Pressurized Water Reactor) and to the reactor (in the case of a Boiling Water Reactor).

The purpose of the condensate and feedwater system is to:

1. Condensate steam from the main and feed pump turbines and collect steam drains via the main condenser
2. Remove non-condensible gases from the main condenser
3. Purify and preheat water prior to injection into the reactor vessel
4. Provide an injection path for the High-Pressure Coolant Injection system to the reactor vessel
5. Provide an injection path for the Reactor Core Isolation Cooling system to the reactor vessel
6. Provide a path for returning the Reactor Water Cleanup system to the reactor vessel.

The condensate and feedwater system is an integral part of the reactor plant regenerative steam cycle. The steam exhausted from the low-pressure turbines is condensed in the main condenser and collected in the main condenser hotwell. The condensate collected in the hotwell is removed by the condensate pumps. The condensate pumps provide the driving force for the condensate flow through the steam jet air ejector condensers and steam packing exhauster. Condensate flow is next directed to the condensate deep-bed demineralizers which purify the condensate water through ion exchange and filtration. Condensate booster pumps take suction from the demineralizers and maintain the driving force of the condensate flow through strings of low-pressure feedwater heaters. The feedwater heaters take extraction steam and hot water from the main turbine and moisture separator reheaters to further raise the condensate temperature. The feedwater pumps take suction from the low-pressure feedwater heaters and develop system pressure high enough to inject into the reactor pressure vessel. The discharge of the feedwater pumps is directed to the two high pressure feedwater heaters. This final stage of feedwater heating is provided by extraction steam from the high-pressure turbine. High-temperature and pressure feedwater is directed to two feedwater lines that penetrate the primary containment.

2.1 Main Condenser and Condenser Hotwell

The main condenser receives cooling water from the Circulating Water System. Circulating water flows through the condenser tubes, condensing the low-pressure turbine exhaust steam surrounding the tubes. During normal operation, steam from the low-pressure turbine is exhausted directly downward into the condenser shells through exhaust openings in the turbine casing. The condenser unit also serves as a heat sink for other systems, including exhaust steam from the reactor feed pump turbines, turbine bypasss steam, cascading low-pressure heater drains, air ejector condenser drains, steam packing exhauster condenser drains, and feedwater heater shell operating vents. The condenser hotwells are incorporated in the bottom of each condenser shell and serve as collection points for all condensate.

2.2 Condensate Pumps

Condensate (CND) pumps (at minimum of two) provide the motive force required to remove water (condensate) from the condenser hotwell to the condensate booster pumps at sufficient pressure to ensure adequate net position suction head. These pumps are stage pumps that can pump water at different capacities and are operated at approximately 200 psig. The condensate booster pumps take water from a common supply header downstream to the demineralizers and provide the required net positive suction head to the reactor feed pumps. Each pump is a motor-driven horizontal centrifugal pump type.

2.3 Condensate Demineralizers

The function of the condensate demineralizers is to remove dissolved and suspended impurities from the condensate. The condensate demineralizers, along with the reactor water cleanup system, serve to purify the steam cycle water and maintain the reactor water quality limits under startup and normal operating conditions.

2.4 Low Pressure Feedwater Heaters

Feedwater (FW) heater extraction steam provides for heating of the feedwater to improve plant efficiency. Extraction steam enters the feedwater heater via two penetrations in the upper section of the heater. Upon entering the heater, the steam is directed at right angles to the point of entry by impingement plates. The impingement plates, along with internal baffling, forces the steam to flow around the upper rows of feedwater heater tubes. When the extraction steam gives up its latent heat of vaporization to the feedwater, the steam condenses and falls to the bottom of the heater forming the heater drains. The heater drains accumulate in the bottom of the heater where they flow around the feedwater heater tubes on the way to the drain cooler section.

2.5 Reactor Feedwater Pumps, Heaters, and Heater Drains

Reactor feedwater pumps (RFPs) take heated feedwater from the outlet of the low-pressure feedwater heaters and provide the driving force necessary to supply water to the reactor vessel. Each RFP is a horizontal, centrifugal, single-stage pump driven by a variable speed steam turbine and each pump is rated at 67% of system capacity. The RFPs have low-suction pressure. The RFPs lead to high-pressure feedwater heaters. High-pressure feedwater heating consists of two identical parallel strings of heaters and valves. Each string consists of a vertically mounted feedwater heater and an inlet and outlet isolation valve. As with the low-pressure heater string, the high-pressure heaters are equipped with a bypass valve. The high-pressure heaters operate in the same manner as the low-pressure heaters. The term “high pressure” originates from the location of the heaters in the condensate and feedwater system and the high-pressure extraction steam used for heating. Both feedwater lines contain flow elements after the outlet isolation valve.

Feedwater heater drains collects condenses as the extraction steam gives up the heat to the feedwater. The feedwater heater utilizes a cascading drain system with the drain flow from the highest pressure and temperature heaters flowing successively to the next lowest pressure heater. The heater drain cooler drains into the main condenser. An example of instrumentation on the condensate and feedwater system at one of the Exelon’s nuclear power plant is presented in Table 1.

Table 1. Condensate and Feedwater Instrumentation at an Exelon’s Nuclear Power Plant.

Asset Name	Asset Tag	Units
Plant CND Pump	Pump Active Thrust Bearing Material Temperature	Deg ^oF
Plant CND Pump	Suction Temperature 1	Deg ^oF
Plant CND Pump	Suction Vessel Level 1	in.
Plant CND Pump	Suction Temperature 2	Deg ^oF
Plant CND Pump	Gross Load	MW
Plant CND Pump	Motor NDE Bearing Material Temperature	Deg ^oF
Plant CND Pump	Suction Vessel Level 2	In.
Plant CND Pump	Motor DE Bearing Material Temperature	Deg ^oF
Plant FW Booster Pump	Pump Active Thrust Bearing Material Temperature 1	Deg ^oF
Plant FW Booster Pump	Common Discharge Header Pressure	psig
Plant FW Booster Pump	Pump Active Thrust Bearing Material Temperature 2	Deg ^oF
Plant FW Booster Pump	Pump NDE Bearing Material Temperature	Deg ^oF
Plant FW Booster Pump	Common Suction Header Pressure	psig
Plant FW Booster Pump	Gross Load	MW
Plant FW Booster Pump	Motor NDE Bearing Material Temperature	Deg ^oF
Plant FW Booster Pump	Motor DE Bearing Material Temperature	Deg ^oF
Plant FW Booster Pump	Pump DE Bearing Material Temperature	Deg ^oF

Plant FW Pump	Pump Case Outer Temperature 2	Deg ºF
Plant FW Pump	Lube Oil Cooler Discharge Temperature	Deg ºF
Plant FW Pump	StepUp Gear Outerbound Output Bearing Material Temperature	Deg ºF
Plant FW Pump	Discharge Pressure	psia
Plant FW Pump	StepUp Gear Outerbound Input Bearing Material Temperature	Deg ºF
Plant FW Pump	Motor Outerbound Bearing Material Temperature	Deg ºF
Plant FW Pump	StepUp Gear Innerboudn Input Bearing Material Temperature	Deg ºF
Plant FW Pump	Pump Case Outer Temperature 1	Deg ºF
Plant FW Pump	Discharge Flow 2	K#Hr
Plant FW Pump	Pump Thrust Bearing Active Material Temperature 1	Deg ºF
Plant FW Pump	Gross Load	MW
Plant FW Pump	Suction Temperature 1	Deg ºF
Plant FW Pump	Feedwater Control Valve Position	%
Plant FW Pump	Motor Innerbound Bearing Material Temperature	Deg ºF
Plant FW Pump	Discharge Flow 1	K#/HR
Plant FW Pump	Booster Feedwater Pump Recirculation Flow	klbm/hr
Plant FW Pump	Discharge Flow 3	M#/H
Plant FW Pump	Pump Innerbound Bearing Material Temperature	Deg ºF
Plant FW Pump	Discharge Temperature	Deg ºF
Plant FW Pump	StepUp Gear Innerbound Output Bearing Material Temperature	Deg ºF
Plant FW Pump	Pump Outrebound Bearing Material Temperature	Deg ºF
Plant FW Pump	Discharge Pressure 2	psia
Plant FW Pump	Discharge Pressure 3	psig
Plant FW Pump	Discharge Temperature 2	Deg ºF
Plant FW Pump	Discharge Flow 4	K#Hr
Plant FW Pump	Discharge Flow 5	Klb/hr
Plant FW Pump	Discharge Flow 6	Mlbm/hr
Plant FW Pump	Feedwater Bypass Control Valve Position	%
Plant Main Condenser	Gross Load	MW
Plant Main Condenser	Main Steam Pressure	psia
Plant Main Condenser	Condensate Flow	klbm/hr
Plant Main Condenser	Low Pressure 1 Exhaust Steam Temperature	Deg ºF
Plant Main Condenser	Low Pressure 1 Condenser BackPressure	in.Hg
Plant Main Condenser	Circulating Water Waterbox A Inlet Temperature	Deg ºF
Plant Main Condenser	Make Up Flow	GAL
Plant Main Condenser	Mode Tag	MWt
Plant Main Condenser	Low Pressure Bowler Pressure 1	psia
Plant Main Condenser	Low Pressure 1 Condenser Vacuum 2	Hg
Plant Main Condenser	Condensate flow 2	K#Hr
Plant Main Condenser	Circulating Water Waterbox A Discharge Temperature 2	Deg ºF
Plant Main Condenser	Circulating Water Waterbox A Inlet Temperature 2	Deg ºF
Plant Main Condenser	Hotwell Low Vacuum Level 1	In

Plant Main Condenser	Low Pressure 1 Condenser Vacuum 1	in.Hg
Plant Main Condenser	Hotwell Condensate Temperature 1	Deg ºF
Plant Main Condenser	Circulating Water Waterbox B Discharge Temperature 2	Deg ºF
Plant Main Condenser	Circulating Water Waterbox B Discharge Temperature 1	Deg ºF
Plant Main Condenser	Circulating Water Waterbox A Discharge Temperature 1	Deg ºF
Plant Main Condenser	Barometric Pressure	psia
Plant Main Condenser	Low Pressure 3 Condenser Vacuum 1	in.Hg
Plant Main Condenser	Low Pressure 3 Exhaust Stream Temperature 1	Deg ºF
Plant Main Condenser	Low Pressure 2 Condenser Vacuum 1	in.Hg
Plant Main Condenser	Low Pressure 2 Exhaust Stream Temperature 1	Deg ºF
Plant Main Condenser	Circulating Water Waterbox B Discharge Temperature 4	Deg ºF
Plant Main Condenser	Circulating Water Waterbox A Discharge Temperature 3	Deg ºF
Plant Main Condenser	Circulating Water Waterbox B Discharge Temperature 3	Deg ºF
Plant Main Condenser	Circulating Water Waterbox A Discharge Temperature 4	Deg ºF

3. WIRELESS TECHNOLOGIES

There cannot be one wireless technology supporting all applications. The co-existence of different wireless technologies is discussed in [3]. For the purpose of this research, the focus will be in the DAS to support wireless sensor installation at a plant site to communicate the information to a remote location for decision-making.

3.1 Distributed Antenna System

A DAS is a solution to provide indoor cellular coverage. The basic idea is to divide the coverage area into smaller coverage regions, each covered by a DAS. The division of coverage area into smaller regions improves the performance in terms of path loss and transmission power. A DAS does not generate a signal but is instead fed a core cellular network such as eNodeB (eNB). The signal is then distributed to the various antennas in the system. In a DAS environment, both the eNB and the mobile station require less power which, in turn, improves the battery life of the mobile station (MS).

DAS networks are typically used to accommodate carrier-based cellular networks in indoor environments. Although potentially broader in application than discrete systems due to their ability to accommodate several radio signals, this comes with additional planning, design, and operations complexities. Each radio spectrum has different characteristics for coverage and capacity that need to be accommodated by the system. In a DAS, several antenna elements are connected to the base station through coaxial cable or fiber optics. The DAS is mainly categorized into three types, which are detailed in the sections below.

3.1.1 Passive DAS

A passive DAS [4] requires more power from the eNB, fulfilling the power requirement with the coaxial cables and splitters in the building. Coaxial comes with different thicknesses according to requirement and load. Splitters are attached to coaxial cables to feed power to several antenna elements. Passive DASs are ideal for small buildings without much metal, masonry, or concrete to block the radio-frequency (RF) signals. Moreover, passive a DAS supports multiband operations (which helps to install different wireless technologies) and filters are used to separate different frequency bands. They are simply repeaters for signals to or from an outside antenna and are the smallest and easiest to design, but due to the rigidness of coaxial cable, the installation may take time. The cable loss associated with a passive DAS is high, which affects the uniformity of coverage in buildings.

Passive DAS advantages:

a) Simple to deploy but time consuming due to coaxial cable rigidness
b) Suitable for harsh environments such as industrial plants and garages, etc.
c) Components from different vendors are easily compatible with one another
d) Can build multiple wireless technologies.

Passive DAS limitations:
a) More cable loss due to coaxial cables
b) More signal attenuation at higher frequencies, which affects quality of service
c) High power requirement from base station
d) Difficult to build a balanced link budget for coverage.

3.1.2 Active DAS

An active DAS [5] consists of RF components which are interconnected with fiber optic and coaxial cables, the main unit, an expansion unit, and a remote unit. The architecture of the active DAS is shown in Figure 2.

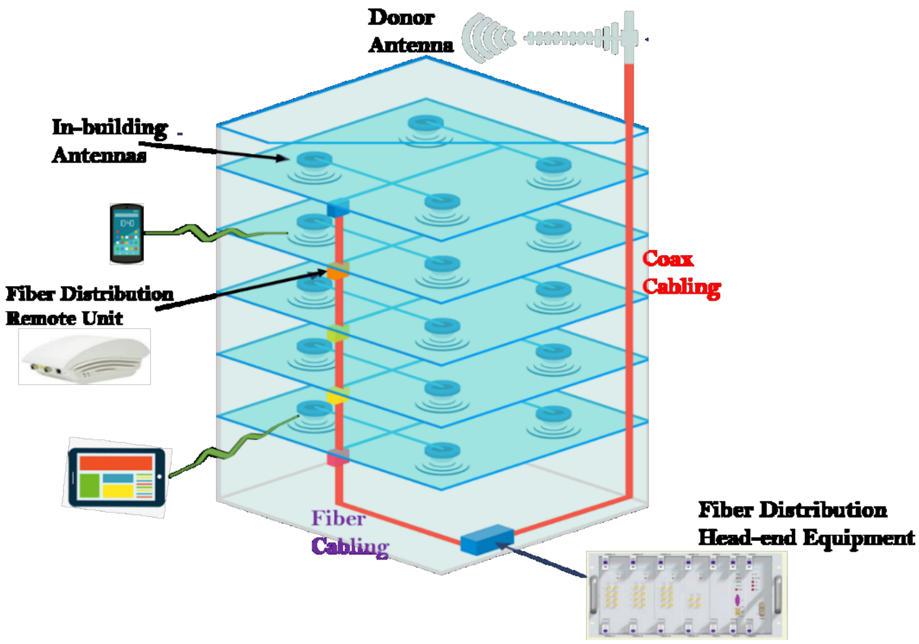

Figure 2. Active Distributed Antenna System [5].

A. ***Main Unit***:
The central part of the network provides connectivity between base station (BS) and an expansion unit via fiber optic cable. The main unit monitors the DAS by generating alarming signal to the BS when any defect occurs. In addition, the status of the whole system can be seen at the main unit using light emitting diodes, a liquid crystal display, or with the help of a connected PC, depending on the system's manufacturer.
B. ***Expansion Unit***:
The expansion unit converts optic signals from the main unit to an electrical signal, which feeds the remote unit. A maximum of four expansion units can be connected to the main unit at a typical distance of 1.5 km from the main unit with multimode fiber.
C. ***Remote Unit***:
A remote unit is connected to an expansion unit through information technology cables or CAT 5. A maximum of five remote units can be connected to an expansion unit without external power since the expansion unit delivers the DC power within the cable. The remote

unit is connected to antennas, then it converts the electric signal from the expansion unit to a downlink radio signal for the MSs, then to an uplink radio signal from the MSs to an electric signal for the expansion unit. The uplink losses are reduced by connecting antennas close to the remote unit.

Active DASs are better suited for larger spaces, or for spaces constructed out of materials that block RF signals. They convert the RF signal to a digital signal for better distribution, then use fiber optic or ethernet cables to distribute the signal. This is the costliest of the distribution designs, but the use of fiber optic cables minimizes cable loss and provides uniform coverage in the building with less power required from the BS.

Active DAS advantages:

a) Low RF losses due to use of active components and fiber optic cable
b) Provides uniform coverage
c) Suitable for medium to large buildings like hospitals, shopping malls, etc.
d) Low power requirements and removes the need for cooling systems.

Active DAS limitations**:**

a) Much more expensive than other solutions
b) Requires specialized equipment and cabling such as fiber optic cables
c) Longer deployment time.

A hybrid DAS combines the advantages of passive and active DAS, and while they are cheaper than active DAS, they are more complicated to install.

3.1.3 MROU architecture

Heterogeneous wireless networks [3] with a range of frequencies and applications need DAS technology as the backbone network to connect to the internet or to a cloud. DAS technology acts as a bridge between the core cellular network and the heterogenous network. DAS [4] also supports multiple cellular carriers which can be extended, establishing good cellular network coverage inside buildings and at public places. In addition, using DAS with the MROU (shown in Figure 3) also reduces the cabling cost which can occur due to multiband wireless network.

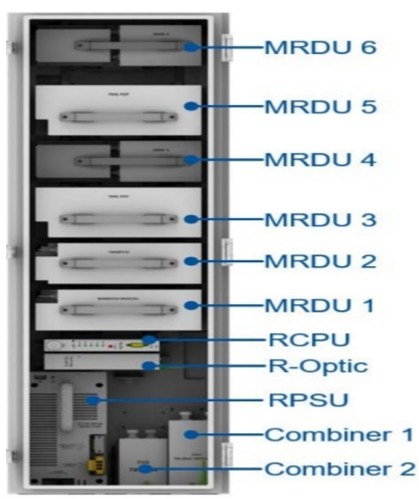

Figure 3. MROU architecture [3].

The essential unit in building a DAS system is MROU, which receives an optical signal from ODU and converts it to RF in the Remote Optic module [3]. The RF signals are fed to the Remote Drive Units (MRDU) where the RF signals are filtered to remove out-of-band signals (e.g. to amplify cellular signal, remove long-range wide-area network signals). The signals from multiple MRDUs with a desired band are combined using a multiplexer and eventually fed to the antenna port. Table 2 shows the slot configuration of MROU.

Table 2. MROU Slot configuration.

5W ROU	Recommended Configurations
MRDU1 (Bottom most)	800 Sprint/850C only
MRDU2	1900P only
MRDU3	700LTE_A only
MRDU4	AWS_A only
MRDU5	700LTE_B or 700PC_800PS or 2500 or 2300
MRDU6 (Topmost)	AWS_B or 2300 or 900 or 2500
Add-on Remote	VHF/UHF

4. SUMMARY AND PATH FORWARD

In the report, the plant system identified for achieving predictive maintenance is described along with current level of instrumentation. The plant system identified is condensate and feedwater system. A brief overview on the purpose of the condensate and feedwater system along with descriptions on main components of the system are presented. The current level of instrumentation on the condensate and feedwater system provides the data collected by the partnering nuclear plant owner. Some of the data are collected as part of the plant process on a continuous basis and some data are collected periodically as part of preventive maintenance strategy.

As part of the path forward, based on the range of data values, a data completeness evaluation will be performed to identify a gap in the data and researchers will make recommendations to install additional sensor modality to bridge the gap in the data.

5. REFERENCES

[1] Manjunathan, K. A., and Agarwal, V. (2019). Review of Wireless Communication Technologies and Techno-Economic Analysis. Idaho National Laboratory, INL/EXT-19-53966, May 2019.

[2] General Electric Systems Technology Manual, Chapter 2.6. Condensate and Feedwater Systems. U.S. Nuclear Regulatory Commission. Revision 9, 2011.

[3] Lowe, C.L., Kiger, C.J., Jackson, D.N. and Young, D.M., Implementation of Wireless Technologies in Nuclear Power Plants' Electromagnetic Environment Using Cognitive Radio System.

[4] https://cdn.everythingrf.com/live/DASfrIoTCllulrWrlss%20(arrf).pdf

[5] Niu, Yong, Yong Li, Depeng Jin, Li Su, and Athanasios V. Vasilakos. "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges." *Wireless Networks* 21, no. 8 (2015): 2657-2676.