EXECUTIVE SUMMARY

Software-defined Wireless Decentralized Building Management System

ESTCP Project EW-201410

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AHU	Air Handling Unit
API	application programming interface
ATO	Authority to Operate
BMS	building management system
cf	cubic foot/feet
DoD	U.S. Department of Defense
ESCO	energy services company
ESPC	Energy Savings Performance Contract
ESTCP	Environmental Security Technology Certification Program
GHG	greenhouse gas
HTML	Hypertext Markup Language
HVAC	heating, ventilation, and air conditioning
IGA	investment grade audit
kWh	kilowatt hour(s)
M&V	measurement and verification
MCU	microcontroller
MHz	megahertz
O&M	operations and maintenance
SCIF	Sensitive Compartmented Information Facility
sqft	square foot/feet
V	volt

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1.0 INTRODUCTION

To improve the return on investment (ROI) of a particular building energy performance upgrade, either (1) the lifetime cost of the upgrade must be reduced, and/or (2) the lifetime building energy usage must be reduced. Competing building management system (BMS) solutions tend to focus on reducing energy usage rather than reducing the lifecycle cost of installing, maintaining, and upgrading a BMS installation.

The existing state-of-the-art BMS typically consists of one or more "field controllers" inside a building that runs the control software. This controller is then connected to sensor and control devices throughout the building typically using twisted-pair wiring. For larger buildings, multiple field controllers must be installed and networked to each other, and then to higher level "network controllers" if a site-wide management system is used. This typical BMS configuration has several distinct limitations versus the proposed BMS architecture to include the following:

1. **Installed cost:** Installing and commissioning a typical BMS is extremely time-intensive and expensive. This cost is especially burdensome in three specific cases: (a) small (< 50,000 square feet [sqft]) buildings where the cost of the controllers dominate the overall hardware cost of the BMS (74% of all small federal buildings are under U.S. Department of Defense [DoD] control); (b) retrofit applications where existing twisted-pair wiring does not exist everywhere in the building; and (c) complex heating, ventilation, and air conditioning (HVAC) setups, with combinations of multiple HVAC systems such as chillers, boilers, packaged units, and window/space units in the same building.

2. **Maintainability/upgradability:** In order to upgrade the typical BMS with improved control algorithms, the field controllers must typically be replaced. As a result, control algorithm improvements are not normally made outside of major improvement projects, since significant energy performance improvements are required to justify the hardware upgrade costs.

3. **Scalability:** As improved sensor/control technology becomes available or becomes more cost-effective over time, existing BMSs cannot easily handle small incremental scaling and typically require significant upgrades to the controllers when additional sensor types are added.

4. **Energy auditing:** Due to the fundamental bandwidth limitations of twisted-pair bus connections, poor or non-existent wireless performance, and fundamental architecture of the typical BMS, existing BMSs do not collect performance data well enough to provide auditing or measurement and verification (M&V) data for energy services companies (ESCOs) to use.

The 1993 Commercial Buildings Energy Consumption Survey (CBECS) Federal Building Supplemental Survey estimates 45% of DoD floorspace is made up of small (< 50,000 sqft) buildings, of which only 22% had energy management systems at the time. Considering the age of this last survey, the portion of small buildings with energy management systems has most likely increased to closer to 40%. Installing advanced BMSs in this sector would provide at least an 8% energy savings when replacing an optimized non-BMS control system, and more than 30% energy savings when replacing building controls that lack an off-hour energy reduction scheme based on simulations.

At a conservative yearly energy cost of $1.40/sqft, this equates into an opportunity for $60 million–$227 million in utility savings per year for the DoD small building inventory alone. Additionally, installing BMSs into a greater portion of small DoD buildings would provide other benefits such as reduced operations and maintenance (O&M) costs.

2.0 OBJECTIVES

The overall objective of this demonstration was to prove the viability of replacing existing BMSs based on cost-savings alone. Four performance objectives were set for this demonstration:

1. **Energy and utility savings:** The most fundamental goal of the wireless BMS technology is to reduce energy usage and costs. Using a BMS to implement night setback alone will typically yield a 15% energy savings. This performance objective was to target at least a 15% overall energy reduction compared to baseline.

2. **Payback period:** To entice an ESCO to utilize a new technology in a traditional performance contract, a simple payback of ten years is typically necessary to make it attractive. This performance objective was to verify a simple payback of ten years based on utility savings alone.

3. **Security:** Due to the advanced technologies used in this BMS such as wireless and network-based communications, there are substantial security requirements. This performance objective aimed to meet and exceed all security requirements of the Air Force and DoD, while simultaneously providing substantial monitoring and control benefits. A full site Authority to Operate (ATO) would be obtained during the demonstration.

4. **O&M:** At most DoD facilities, O&M responsibilities are outsourced to a contractor. Due to the tight relationship between O&M activities and energy usage, many ESCOs are looking to include O&M services as part of the performance contract. This larger contract size can increase the available capital for new equipment at the start of the contract. This performance objective was to demonstrate any tangible benefit the BMS can provide for O&M activities can directly impact the potential adoption for performance contracts.

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3.0 TECHNOLOGY DESCRIPTION

Competing systems have been building on-top of legacy platforms for decades, and many modern concerns such as wireless and security have never been properly addressed at a low level. Additionally, communication application programming interfaces (APIs) and hardware power requirements have been constantly growing to handle additional complexities, and result in higher-cost systems, which are increasingly difficult to design and install.

Halo/S™, Paragon's next-generation wireless BMS platform, has been designed entirely from the ground up, to address the significant limitations of competing systems. This platform encapsulates data acquisition and controls into a single unified ecosystem. There are five main design differences between Halo/S and the architectures of state-of-the-art competing BMSs:

1. **Decentralized:** Halo/S has been designed to run on an ultra-low cost (~$0.50) 8-bit 8051 microcontroller (MCU), allowing every sensor and control to be made "smart." This allows sensors, controls, and interfaces to execute their own software and communicate directly with each other, eliminating the need for centralized controllers.

2. **Industry-leading wireless:** A proprietary 915 megahertz (MHz) wireless protocol has been developed, which provides ultra-low power usage (seven-year battery life on AAA batteries). This is achieved with an innovative time-synced network that allows end devices to wake up for only 1 millisecond (ms) every 2 seconds to check for incoming requests. The wireless system also provides vastly improved indoor range versus competitors (four times the indoor range of ZigBee®), through the use of a first-of-its-kind multiple data rate protocol.

3. **Software-defined:** All hardware devices (sensors, interfaces, controls, gateways, etc.) have an identical Halo/S control module with identical firmware onboard. Actual functionality is then provided by higher level software, which can be configured and remapped on-the-fly and over-the-air.

4. **Industry-leading security:** AES-256 encryption/authentication is used for all Halo/S communication. Multiple keying allows messages to be encrypted at multiple levels, allowing for advanced security designs with multiple access privileges.

5. **Merging of data acquisition and controls:** By providing built-in data acquisition capabilities to every hardware device, the Halo/S platform effectively merges full-featured data logging and monitoring directly with the BMS capability.

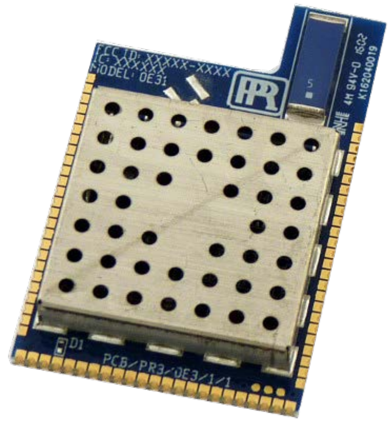

Figure 1. OE3x Module

3.1 HARDWARE OVERVIEW

On top of the Halo/S software platform, a new wireless protocol has been developed to drastically improve indoor range and battery life over existing state-of-the-art, low data rate, wireless protocols such as 802.15.4. A Silicon Labs 8051 MCU is used in combination with a sub-gigahertz (GHz) radio, utilizing the 915 MHz industrial, scientific, and medical (ISM) band for communication. This integrated circuit (IC), along with support components, makes up the OE3x module (see Figure 1), which is then used for every device in the ecosystem. Using an identical module on every device provides several advantages to include the following:

- Module production volumes are higher, reducing assembly and component costs.
- Federal Communications Commission (FCC) and other wireless certification costs are
- drastically reduced, as only a few module certifications are needed (separate certifications are needed for antenna variants).
- Firmware maintenance and support costs are reduced.
- Third parties can develop products utilizing the module to create their own fully-compatible Halo/S devices.

3.2 HARDWARE DEVICES

All hardware devices used in the BMS are built using a common OE3x module component. Each unique device is required in order to provide specific input and/or output hardware for a specific function. Because all intelligence and configurability for the devices are located entirely in software, only one version of each device is needed to cover all potential HVAC systems. Some of the devices may have lower-end versions in order to strip out some hardware costs not needed for certain applications.

1. **Gateway:** Each building typically requires a gateway (Figure 2) to create a wireless network, to provide a gateway from the wireless network to a wired (Ethernet) network. The gateway also provides storage for logging/trending datasets on its onboard flash memory.
2. **Super-Gateway:** Super-Gateway devices provide additional capability and manage additional tasks such as automated backups and authentication for users on the system. It also typically serves up the Hypertext Markup Language (HTML) files needed by user workstations for all Human Machine Interface (HMI).
3. **Sensors:** A wide array of sensor devices (Figure 3) are available for use: ambient temperature, ambient humidity, ambient light, occupancy, pipe temperature, airstream temperature, current/power, pulse count, carbon dioxide, and many others. All sensors are packaged into a similar base case design.
4. **Thermostats/temperature controllers:** Thermostats or temperature controllers (Figure 4) provide a basic liquid crystal display (LCD) screen and button inputs to allow users to interact with the device. A temperature sensor, humidity sensor, and control relays are present to directly control both low (24-volt [V]) and high (240-V) voltage contacts on equipment.
5. **Third-party controllers:** Controller hardware from third-party manufacturers (Figure 5) is utilized for more complex equipment control such as Air Handling Unit (AHU), boiler, and chiller controls. Many manufacturers now offer low-cost equipment level controls, which can be cost-effectively integrated with a Paragon Super-Gateway to provide equivalent performance to a full Paragon hardware solution. The small additional costs from using this "hybrid" approach on more complex equipment control is minimal, and often allows local controls contractors to be utilized for installation of the equipment-level controls at DoD sites.

Figure 2. Gateway

Figure 3. Sensor

Figure 4. Thermostat

Figure 5. Third-party Controller

3.3 SOFTWARE ARCHITECTURE

The high-level software for the BMS is broadly separated into "equipment control" and "energy control" domains (see Figure 6). The equipment control domain is responsible for the hardware abstraction level for low-level equipment control, and the high-level energy domain controls overall energy savings and site-level strategies. This split allows for several advantages to the overall control topology to include the following:

- **Excellent separation of duties for ESCO responsibilities:** By containing low-level equipment control and sequences of operation to the “equipment control” domain, ESCOs can retain tight control over energy usage while utilizing local controls contractors to maintain basic operation.
- **Upgrades can be easily done without impacting energy efficiency:** Equipment level controls can be upgraded to handle changes to HVAC equipment, while exposing the same hardware abstraction API to the energy control domain.
- **Energy control design complexity is drastically reduced:** The energy control domain is further broken down into comfort controllers, energy management blocks, and site controllers. This split allows complex control networks to be broken down into simpler “building blocks.” The building blocks can be quickly assembled into a complex system and automatically eliminate all high-level configuration during setup.

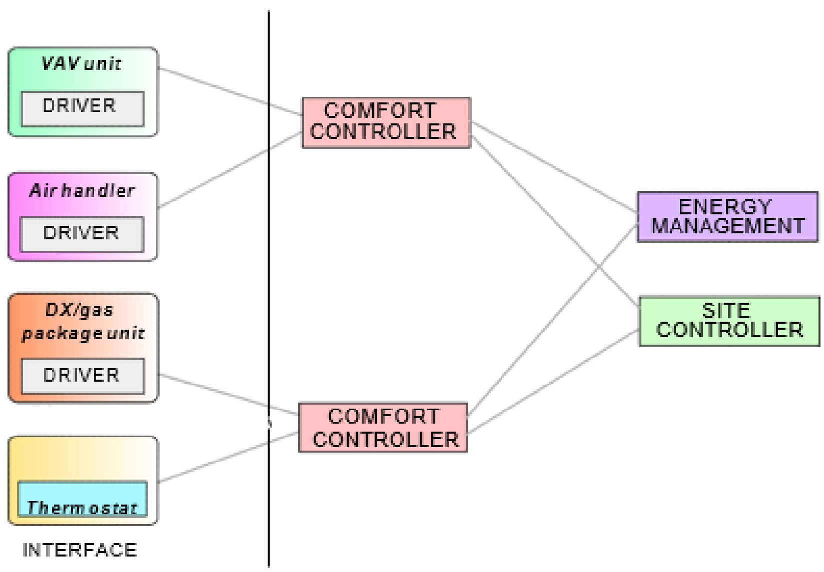

Figure 6. Separation of Energy and Equipment Control

3.4 HIGH-LEVEL SOFTWARE

All high-level interaction with the BMS is done through a web browser using HTML5. Although many competing BMSs are controlled through browser-based interfaces, Halo/S is controlled in a much different way. Competing systems typically require a browser to load custom HTML pages from a network controller, in which custom HTML pages are specifically crafted to request specific information from the user. This feedback from the operator is then processed by internal firmware on the network controller to perform some specific action.

The wireless BMS architecture eliminates the need for network controllers or any custom firmware to process operator input. Instead, gateway devices serve up an HTML5 interface to the operator’s browser, with a complete Halo/S kernel coded in JavaScript. The user’s browser then uses Asynchronous JavaScript and XML (AJAX) to directly communicate through the gateway using Halo/S bytecode. This approach provides several significant advantages over the traditional method to include the following:

- No custom processing firmware is needed on "network controllers," eliminating the need for this component.
- System functionality is not limited to the specific HTML and firmware in the network controller, as direct Halo/S communication can be established with any device allowing unlimited flexibility.
- Low-level network communication is drastically simplified; all devices only need to route Halo/S bytecode packets to handle everything from complete control algorithm changes to firmware updates.

The browser software is organized into "widgets," each of which handles a portion of the overall software functionality:

- **ServerManager:** manage user authorizations, server management, data backups, and other required system administration functionality.
- **SetupDevices:** used to set up devices and configure them into a network. This widget includes all security setup, firmware management, and other low-level tasks needed on the device level.
- **DataRecorder:** primarily used for data logging setup, data charting, and data exporting.
- **SystemModeler:** graphically creates the building layout to help visualize equipment during control commissioning.
- **SystemController:** the HVAC/lighting control setup software, typically used by the installer and operations personnel.
- **SystemAnalyzer:** provides a high-level dashboard for building tenants or other "casual" users to access data from the BMS and perform high-level analysis on the information.
- **SoftwareDeveloper:** utilized by the installing contractor for creating customized control algorithms and making them available for installation using SystemController.

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4.0 PERFORMANCE ASSESSMENT

4.1 BASELINE ANALYSIS

A summary of all baseline HVAC performance findings is shown in Table 1. In general, no energy savings controls were present on any of the demonstration buildings. It is also worth noting that this type of performance analysis is required during the investment grade audit (IGA) phase of an Energy Savings Performance Contract (ESPC). The quality of the collected baseline data using the wireless BMS equipment demonstrates the ability to meet the requirements for IGA data collection by an ESCO.

Table 1. HVAC Performance Summary for Demonstration Buildings

Building	Usage	Occupied schedule	Night setback	Proper lights shutoff	Proper space conditions	Economizer works	Proper blower shutdown	HW/CWH temperature reset	Enthalpy optimization
4001	Office	*M-F, 0530-1700*	No	Yes	Yes	N/A	N/A	N/A	N/A
4004	Office	*M-F, 0530-1700*	Some	Yes	No	N/A	N/A	N/A	N/A
4012	Office	*M-F, 0530-1700*	No	Yes	Yes	No	No	No	No
4023	Office	*M-F, 0530-1700*	No	Yes	Yes	N/A	N/A	N/A	N/A
4028	Office	*M-F, 0530-1700*	No	Yes	Yes	N/A	N/A	N/A	N/A
4029	Office	*M-F, 0530-1700*	No	Yes	No	No	No	No	No
4032	Office	*M-F, 0530-1700*	No	Yes	Yes	N/A	N/A	N/A	N/A
4048	Shower	*S-S, 0500-2100*	No	Yes	Yes	N/A	N/A	N/A	N/A
4049	Gym	*S-S, 0530-2100*	No	Yes	Yes	N/A	N/A	N/A	N/A
4057	Office	*M-F, 0530-1700*	No	Yes	Yes	No	No	No	No
4064	Office	*M-F, 0530-1700*	No	Yes	Yes	No	No	No	No
4068	Office	*M-F, 0530-1700*	No	Yes	Yes	N/A	N/A	N/A	N/A
4069	Office	*M-F, 0530-1700*	No	Yes	Yes	N/A	N/A	N/A	N/A
4077	Warehouse	*None*	No	Yes	Yes	N/A	N/A	N/A	N/A
4078	Warehouse	*None*	No	Yes	Yes	N/A	N/A	N/A	N/A
4079	Office	*M-F, 0530-1700*	No	Yes	Yes	N/A	N/A	N/A	N/A

Existing electricity and gas meters were used in conjunction with 349 Paragon sensors to accurately measure the baseline energy usage for all buildings. This baseline usage data was utilized for the final savings and payback calculations.

4.2 THERMOSTAT CONTROL RETROFIT

After retrofitting certain thermostatically-controlled buildings, occupied space temperature and humidity were monitored to confirm the comfort targets were being met. Energy savings configurations such as night setback and humidity optimizations were also analyzed.

The team then analyzed the reduction in energy use after the thermostat retrofits. The team primarily utilized Building B4068 for this analysis, as it had the most reliable metering data as well as the best physical access. Electricity and gas usage were charted before and after the retrofit, and a temperature correlation regression was performed to account for climate effects. A similar approach was used for all thermostatically-controlled building within the demonstration area (see Table 2). Overall electricity savings of 21.8% and gas savings of 39.4% were achieved across the entire demonstration building portfolio.

Table 2. Post-retrofit Savings on Buildings with Thermostatic HVAC Control

Building	Size (sqft)	Baseline usage		Post-retrofit usage		Utility savings		GHG savings
		Electricity (kWh)	Gas (cf)	Electricity (kWh)	Gas (cf)	Electricity (%)	Gas (%)	
B4001	2195	63242	89995	47103	46201	25.5%	48.7%	27.7%
B4004	11798	212364	403691	171920	220653	19.0%	45.3%	22.3%
B4023	3687	66366	151167	50097	78081	24.5%	48.3%	27.9%
B4028	1870	33660	96071	24996	49084	25.7%	48.9%	29.8%
B4032	1803	32454	73923	24086	37771	25.8%	48.9%	29.1%
B4048	2583	67158	207059	50195	106098	25.3%	48.8%	29.6%
B4049	3731	86412	152971	65254	79325	24.5%	48.1%	27.2%
B4057	9898	653957	261475	521035	170460	20.3%	34.8%	20.7%
B4068	1483	17426	62242	12895	31744	26.0%	49.0%	30.8%
B4069	4704	84672	192864	64496	100200	23.8%	48.0%	27.3%
B4077	2450	844	224184	844	195040	0.0%	13.0%	12.4%
B4078	2428	844	223376	844	194337	0.0%	13.0%	12.4%
B4079	3674	66132	150634	49915	77800	24.5%	48.4%	28.0%
Total	***52304***	***1385531***	***2289653***	***1083682***	***1386795***	***21.8%***	***39.4%***	***23.7%***

4.3 AIR HANDLING UNIT (AHU) CONTROL RETROFIT

The team first analyzed the control performance after the Building B4029 AHU controls were replaced with JACE® controllers. At this stage, the JACE controllers were only maintaining a constant comfort setpoint for all occupied spaces.

Once the JACE controllers were confirmed to be properly maintaining comfort levels and following proper sequence of operations, the team used the Super-Gateway controller to implement eight different savings algorithms. Due to HVAC equipment outages, Super-Gateway long-term stability issues, and lack of time before contract end, the team was unable to collect enough performance data after the Super-Gateway installation to confirm savings and performance on the actual installation. Instead, the operation of the Super-Gateway on a bench-test setup was evaluated to confirm the energy savings algorithms behaved as expected. By confirming the Super-Gateway properly controlled all simulated actuators in response to simulated inputs on the bench-test, the team could then “manually” control the building HVAC equipment to replicate the Super-Gateway control and measure the actual energy savings from the building. Simulations could also be done afterward using the theoretical Super-Gateway algorithms.

Table 3 show a summary of the energy savings for all demonstration buildings containing AHUs. Across all demonstration buildings with AHU controls, measurements and simulations show an overall electricity savings of 27.2% and gas savings of 41.9%.

Table 3. Post-retrofit Savings on Buildings with AHU Control

Building	**Size (sqft)**	**Baseline usage**		**Post-retrofit usage**		**Utility savings**		**GHG savings**
		Electricity (kWh)	**Gas (cf)**	**Electricity (kWh)**	**Gas (cf)**	**Electricity (%)**	**Gas (%)**	
B4012	14028	216278	685515	140581	294772	35.0%	57.0%	39.2%
B4029	19220	548212	788020	361820	354609	34.0%	55.0%	36.0%
B4064	50780	653957	2081980	529705	1415746	19.0%	32.0%	21.5%
Total	***84028***	***1418447***	***3555515***	***1032106***	***2065127***	***27.2%***	***41.9%***	***29.5%***

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5.0 COST ASSESSMENT

A full payback analysis was then run on all buildings in the demonstration area. A full installation quotation for this group of buildings was created based on a full walk-through by a controls technician, followed by a firm fixed cost proposal from a controls subcontractor.

The utility savings for each building were calculated based on simulated savings for each building, factoring in a 20% savings reduction margin. Utility rates of $0.055/kilowatt hour (kWh) and $0.49/therm were used.

Table 4 shows the results from the analysis. Nearly all of the buildings were able to achieve a < 10-year simple payback. The aggregated simple payback achieved was 4.8 years for the demonstration building set. Even though two of the buildings had payback periods > 10 years, most stakeholders would likely prefer to retrofit all building to maintain consistency and improve O&M efficiencies.

Table 4. Simple Payback Analysis on All Demonstration Buildings

Building	Size (sqft)	Electricity savings	Gas savings	Total estimated savings	Total savings with 20% margin	Installed cost	Simple payback (yrs)
B4001	2195	$887.67	$214.59	$1,102.26	$881.81	$4,398.00	5.0
B4004	11798	$2,224.40	$896.88	$3,121.29	$2,497.03	$7,592.00	3.0
B4012	14028	$4,163.36	$1,914.64	$6,078.00	$4,862.40	$47,910.00	9.9
B4023	3687	$894.79	$358.12	$1,252.91	$1,002.32	$3,639.00	3.6
B4028	1870	$476.51	$230.24	$706.74	$565.40	$3,692.00	6.5
B4029	19220	$10,251.56	$2,123.71	$12,375.28	$9,900.22	$47,910.00	4.8
B4032	1803	$460.24	$177.15	$637.39	$509.91	$1,877.00	3.7
B4048	2583	$932.96	$494.71	$1,427.67	$1,142.14	$4,093.00	3.6
B4049	3731	$1,163.64	$360.87	$1,524.51	$1,219.61	$3,583.00	2.9
B4057	9898	$7,310.67	$445.97	$7,756.64	$6,205.31	$18,148.00	2.9
B4064	50780	$6,833.85	$3,264.54	$10,098.39	$8,078.71	$78,036.00	9.7
B4068	1483	$249.19	$149.44	$398.64	$318.91	$1,877.00	5.9
B4069	4704	$1,109.66	$454.06	$1,563.72	$1,250.97	$5,584.00	4.5
B4077	2450	$0.00	$142.81	$142.81	$114.24	$4,522.00	39.6
B4078	2428	$0.00	$142.29	$142.29	$113.83	$4,522.00	39.7
B4079	3674	$891.95	$356.88	$1,248.84	$999.07	$2,927.00	2.9
Total	***136332***	***$37,850.45***	***$11,726.91***	***$49,577.36***	***$39,661.89***	***$240,310.00***	***4.8***

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6.0 IMPLEMENTATION ISSUES

Several important issues outlined below impeded implementation at the test site and should be considered part of the difficulty in applying this technology at DoD sites.

6.1 SECURE AREAS

Two of the demonstration buildings contained Sensitive Compartmented Information Facility (SCIF) areas. Wireless devices are forbidden inside the enclaves and within 3 feet outside of the perimeter walls. For the auditing work, the team opted to not monitor these SCIF areas as a non-wireless hardware option was not available at that time.

6.2 AUTHORITY TO OPERATE (ATO)

For permanent integrated circuit system installations on Air Force sites, an ATO is required by Air Force Civil Engineer Center (AFCEC). The team received a full site ATO for the wireless BMS platform at Tinker Air Force Base (AFB) in May 2017 and estimate approximately 800 man hours were invested in the ATO process for this demonstration. Approximately half of this time was directly related to the ATO process, with the remainder spent on design changes to meet the full ATO requirements. At a rate of $165/hour (hr), approximately $125,000 should be budgeted by contractors to complete the full ATO process.

6.3 CHANGING SITE CONDITIONS

During the demonstration, the team experienced many site condition changes, which limited the testing size. For this project, the team was able to overcome the reduced sample size by utilizing high-resolution simulations to effectively fill in the data holes.

6.4 COMMERCIALIZATION

All hardware and software products utilized in this demonstration are currently in production and available for sale as of fourth quarter (Q4) 2017. During the process of this Environmental Security Technology Certification Program (ESTCP) demonstration, the team began to modify the initial technology transition plan for the technology. However, in trying to tailor the technology for use with performance contracting, a significant need for additional support services related to metering, auditing, controls installation, and M&V became apparent. Paragon is currently working with another ESCO for a larger rollout of the wireless BMS platform as part of an ESPC at Tinker AFB.