



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**BATTLEFIELD MEDICAL NETWORK: BIOSENSORS IN
A TACTICAL ENVIRONMENT**

by

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March 2016

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 2016	3. REPORT TYPE AND DATES COVERED Master's thesis	
4. TITLE AND SUBTITLE BATTLEFIELD MEDICAL NETWORK: BIOSENSORS IN A TACTICAL ENVIRONMENT			5. FUNDING NUMBERS	
6. AUTHOR(S) Ralph R. Montgomery and Yekaterina L. Anderson				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) Lack of tactical health information is an issue that military leaders and healthcare providers face at all organizational levels today. Incomplete or missing treatment information undermines the provision of downrange care at higher echelons. Furthermore, absence of timely, aggregated, and actionable information on combat-related morbidities can affect strategic capacity planning for health resources within the Department of Defense as well as the Department of Veterans Affairs. Using biomedical sensors can mitigate these issues by monitoring health and environmental metrics of personnel operating in tactical settings. This thesis proposes a system-of-sensors concept that addresses both tactical medical treatment and decision-making needs as well as informed strategic planning for health. A literature review on frameworks for networking, information systems, and key health metrics provided guidance for the proposed system. Bench and field experimentation with available sensors served as proof of concept and was used to evaluate sensors for viable use in a maritime environment. Based on this research, the authors were able to determine that the tested devices were not efficacious for a tactical environment as configured. However, the authors submit that if the sensors were reconfigured to synchronize with a mobile smart device that communicates via a mobile ad-hoc network, these sensors could meet the needs of Maritime Interdiction Operations tactical personnel. This is contingent on having an application suite that is capable of collecting data from multiple biomedical sensors regardless of sensor vendor.				
14. SUBJECT TERMS biomedical sensors, traumatic brain injury, VBSS, MIO, remote health monitoring, Zephyr, BioHarness3, TriaX, SIM-G, SIM-P, OBHIT			15. NUMBER OF PAGES 181	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

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requirements for the degree of

MASTER OF SCIENCE IN NETWORK OPERATIONS AND TECHNOLOGY

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Lack of tactical health information is an issue that military leaders and healthcare providers face at all organizational levels today. Incomplete or missing treatment information undermines the provision of downrange care at higher echelons. Furthermore, absence of timely, aggregated, and actionable information on combat-related morbidities can affect strategic capacity planning for health resources within the Department of Defense as well as the Department of Veterans Affairs. Using biomedical sensors can mitigate these issues by monitoring health and environmental metrics of personnel operating in tactical settings. This thesis proposes a system-of-sensors concept that addresses both tactical medical treatment and decision-making needs as well as informed strategic planning for health.

A literature review on frameworks for networking, information systems, and key health metrics provided guidance for the proposed system. Bench and field experimentation with available sensors served as proof of concept and was used to evaluate sensors for viable use in a maritime environment.

Based on this research, the authors were able to determine that the tested devices were not efficacious for a tactical environment as configured. However, the authors submit that if the sensors were reconfigured to synchronize with a mobile smart device that communicates via a mobile ad-hoc network, these sensors could meet the needs of Maritime Interdiction Operations tactical personnel. This is contingent on having an application suite that is capable of collecting data from multiple biomedical sensors regardless of sensor vendor.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANAM	Automated Neuropsychological Assessment Metrics
AP	Access Point
BAN	Body Area Network
BCC	Body-Coupled Communication
BH3	BioHarness 3
BLE	Bluetooth Low Energy
BR	Breathing Rate
BT	Boarding Team
BTM	Boarding Team Member
C2	Command and Control
CENETIX	Center for Network Innovation and Experimentation
CERE	Center for Environmental Restoration Services
CNS	Casualty Network System
CoT	Cursor on Target
DA	Data Accuracy
DOD	Department of Defense
DHA	Defense Health Agency
DU	Data Utility
EHR	Electronic Health Record
HOT-Fit	Human, Organization, and Technology-Fit Framework
HR	Heart Rate
IEEE	Institute of Electrical and Electronics Engineers
IS	Information Systems
IT	Information Technology
ITEF	Integrated Technology Evaluation Framework
ISI	Initial Safety
JTTR	Joint Theater Trauma Registry
LOS	Line of Site
MAC	Media Access Control
MANET	Mobile Ad-Hoc Network
MDR	Military Health System Data Repository
MHS	Military Health System
MIO	Maritime Interdiction Operations
MOC	Medical Operations Center
mTBI	mild Traumatic Brain Injury
OBHIT	Objectives Based Health Information Technology

P2P	Peer-to-Peer
PAN	Personal Area Network
PDA	Personal Digital Assistant
PHY	Physical Layer
PLA	Peak Linear Acceleration
RAG	Received at Gateway
RHIB	Rigid Hull Inflatable Boat
RR	Respiration Rate - interchangeably used with BR
RSSI	Received Signal Strength Indication
S/N	Serial Number
SC-UWB	Single Carrier Ultra-Wideband
SIG	Special Interest Group
SpO2	Peripheral Capillary Oxygen Saturation
TBI	Traumatic Brain Injury
TCCC	Trauma Combat Casualty Care
TNT	Tactical Network Topology
TOC	Tactical Operations Center
TX	Transmit
UAV	Unmanned Aerial Vehicle
VA	Veterans Affairs
VBSS	Visit, Boarding, Search and Seizure
VE	Virtual Extension
VHA	Veterans Health Administration
VOI	Vessel of Interest
WBSN	Wireless Body Sensor Network
WIISARD	Wireless Internet Information System for Medical Response in Disasters
WMN	Wireless Mesh Network
WPAN	Wireless Personal Area Network
WWBAN	Wearable Wireless Body Area Network
XML	Extensible Markup Language
YBI	Yerba Buena Island

ACKNOWLEDGMENTS

The authors would like to acknowledge the men and women of the uniformed services of the United States of America. The motivation behind this work was to continue the goal of incrementally improving the cradle-to-grave care of warfighters deployed, who are in garrison or transitioning to a veteran's status.

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I. INTRODUCTION

To care for him who shall have borne the battle...

—President Abraham Lincoln, 1865

A. BACKGROUND AND STRATEGIC ALIGNMENT

In 1997, Congress mandated that the Department of Defense (DOD) must have a means to track the longitudinal health of service members (National Defense Authorization Act, 1997). This would allow leadership to better understand the health implications associated with military service. Furthermore, this would ensure that our nation would continue to live up to the words made famous by President Lincoln in his second inaugural address—to honor and care for those who have defended our country. To comply with this mandate, the DOD implemented an electronic health record (EHR). This development further set in motion the ability for Defense Health to secure the continuity of care for our military personnel regardless of where the military mission takes them. Most importantly, the advent of EHRs created an opportunity to more transparently transfer medical treatment history documentation from the DOD to the Veterans Health Administration (VHA). This ensured that military personnel would continue to receive medical care for health conditions incurred while on active duty after transitioning from the DOD into the VHA system.

The requirement to document and provide for the medical needs of our service members and veterans from cradle to the grave has drawn attention to gaps in health information. Specifically, Defense Health lacks a means to seamlessly and ubiquitously monitor the health status of individuals from point of injury to the point where they enter the medical treatment system (Miles, 2012). Moreover, as recent conflicts in Afghanistan and Iraq have shown, the lack of timely morbidity reporting resulted in a health system that was underprepared for

the onslaught of medical treatment needs of wounded service members (Defense Health Board, 2015).

This research team proposes that a system of biomedical sensors equipped on service members may offer a viable solution to address the current communication and information gaps. Such a solution would remove barriers healthcare providers face when seeking a thorough injury history. Ultimately, this would provide appropriate and timely medical care as well as facilitate the right-sizing of medical capacity and capabilities. In addition to addressing these gaps, an ideal system of sensors may prove beneficial in a tactical environment, providing decision makers with the needed information to monitor the health and safety of their personnel.

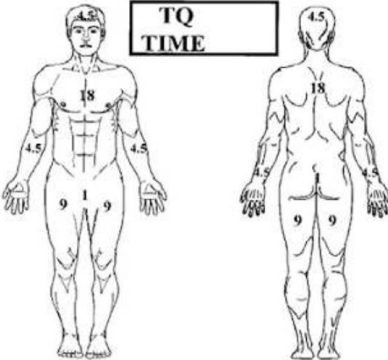
While this research focuses on the tactical implementation of a system of biosensors in the Maritime Interdiction Operations (MIO) realm, this work is germane to strategic Defense Health objectives as outlined in the Quadruple Aim (Military Health System Review, 2014). The impact of continuous health monitoring may positively influence readiness and population health through prevention and timely intervention. Moreover, it may potentially reduce per-capita cost through health system capacity building to decrease purchased care (Figueiredo, Becher, Hoffmann, & Mendes, 2010; Pantelopoulos & Bourbakis, 2010; Military Health System, 2012).

B. PROBLEM STATEMENT

The Department of Defense lacks a means to persistently and ubiquitously conduct telemetric monitoring of the health status of personnel who are operating in a tactical environment. Despite a conventional means of documenting point of injury vital signs and medical treatment rendered (Figure 1), the authors of the Tactical Combat Casualty Care (TCCC) doctrine have conceded that “battlefield documentation is sorely lacking” (Center for Army Lessons Learned, 2012, p. 18). This assertion is supported by a 2007–2010 review of casualty data from the U.S. Military Joint Theater Trauma Registry (JTTR). It showed that 87% of in-

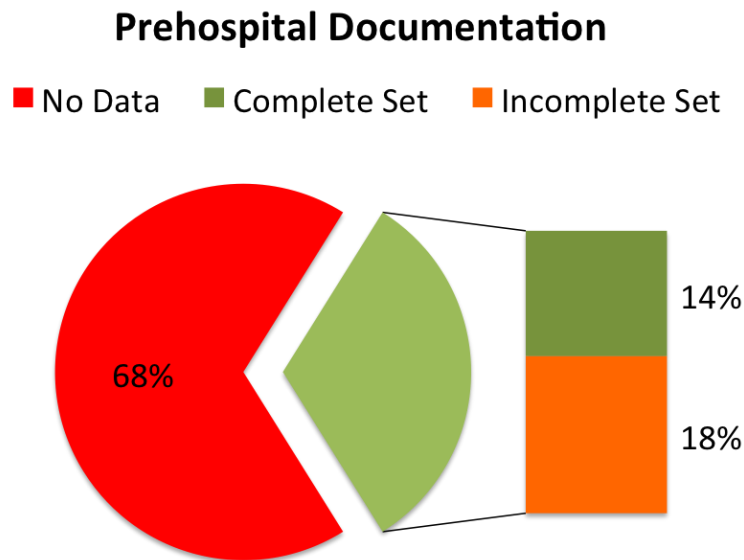
combat zone hospital admissions did not have any prehospital documentation (Eastridge, Mabry, Blackbourne, & Butler, 2011; Therien, Nesbitt, Duran-Stanton, & Gerhardt, 2011). In addition, a separate study showed that only 14% of casualties had a complete set of prehospital vital signs documentation (Figure 2) (Lairret et al., 2012).

Figure 1. TCCC form to document injury, vital signs, and treatment rendered (Department of Army DA FORM 7656s)

<p>Name/Unit _____</p> <p>DTG: _____ ALLERGIES: _____</p> <p>Friendly Unknown NBC</p> <div style="text-align: center;"> <div style="border: 1px solid black; padding: 2px; display: inline-block;">TQ TIME</div> </div>  <p>GSW BLAST MVA Other _____</p> <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 15%;">TIME</td> <td style="width: 15%;"></td> <td style="width: 15%;"></td> <td style="width: 15%;"></td> <td style="width: 15%;"></td> </tr> <tr> <td>AVPU</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>PULSE</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>RESP</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>BP</td> <td></td> <td></td> <td></td> <td></td> </tr> </table> <p style="font-size: small;">DA FORM 7656</p>	TIME					AVPU					PULSE					RESP					BP					<p>A: Intact Adjunct Cric Intubated</p> <p>B: Chest Seal NeedleD ChestTube</p> <p>C: TQ Hemostatic Packed PressureDrsg</p> <hr/> <p>FLUIDS: IV IO</p> <p style="padding-left: 40px;">NS / LR 500 1000 1500</p> <p style="padding-left: 40px;">Hextend 500 1000</p> <p>Other: _____</p> <p>DRUGS (Type / Dose / Route):</p> <p>PAIN _____</p> <p>ABX _____</p> <p>OTHER _____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>First Responder's Name _____</p>
TIME																										
AVPU																										
PULSE																										
RESP																										
BP																										

Source: Center for Army Lessons Learned. (2012). *Tactical combat casualty care handbook*. Retrieved from: http://www.globalsecurity.org/military/library/report/call/call_12-10.pdf

Figure 2. A 2010 study depicted availability of prehospital vital-sign information



Adapted from: Lairet, J. R. et al. (2012). Prehospital interventions performed in a combat zone: a prospective multicenter study of 1,003 combat wounded. *Journal of Trauma and Acute Care Surgery*, 73(2), S38–S42.

The impact of lacking documentation can result in misdiagnoses and ill-informed triage decisions on the battlefield as well as in a pre-surgical setting. Moreover, missing prehospital data can contribute to medical errors and sequelae, potentially resulting in death (Kohn, Corrigan, & Donaldson, 2000; Eastridge et al., 2011; Lairet et al., 2012).

Along with access to complete medical information, there is the strategic imperative to make leaders at all organizational levels better informed about the resources available to them. As a means to align tactical assets with strategic warfighting guidance, it is imperative to acquire a means to persistently monitor force health. This will further address the gap in the FORCEnet expanded concept of connecting individuals to the defense enterprise network (Clark & Hagee, 2005). Having a capability to track and document the health status of tactical personnel employed in operations can offer leadership a holistic picture and provide healthcare providers with more complete information.

C. PURPOSE

The Department of Defense has not fully implemented the use of biosensors for tactical personnel working in high-risk environments. Academic research and private sector implementations of such sensors suggest that the use of this technology is viable for monitoring pertinent health measurements, especially in patients with chronic morbidities (Darwish & Hassanien, 2011; Milosevic, Milenkovic, & Jovanov, 2013; Kartsakli et al., 2015). Biomedical sensors equip healthcare providers with a patient's full spectrum of health information before the injury through the arrival at the ultimate treatment facility. This capability has the potential to contribute to improved health outcomes of injured personnel. The purpose of this research is to

- test biomedical telemetry devices and networking shown to be efficacious for personnel in a tactical environment;
- test the reachback of health status information from such devices to an intermediate or ultimate medical treatment facility; and
- determine an ideal system of biomedical sensors viable for personnel in a tactical environment.

A viable system of sensors must be able to address population health information needs and tactical medical treatment requirements. In addition, this system must be interoperable with the Defense Health's EHR and capable of seamless integration into the defense tactical network infrastructure. Ultimately, this thesis would serve as a foundation for the use of biosensors within the DOD and VHA.

D. STRATEGIC BENEFITS OF RESEARCH

Defense Health implemented a cradle-to-grave information system in lockstep with the congressional mandate to "accurately record the medical condition of members" (National Defense Authorization Act, 1997). This system was designed to track and monitor the health and readiness of our military forces (Director Operational Test and Evaluation, 2002).

Despite the progress made to improve health documentation in garrison as well as in deployed environments, research and experience have shown that gaps continue to exist with medical information handoffs between points of care (Miles, 2012). The issue, rooted in patient safety, is not unique to the military healthcare system. In its 2006 report, the Joint Commission documented a requirement for systematic controls to “provide accurate information about a [patient’s] care” (Patton, 2007, p. 4). Furthermore, Lairet et al. (2012) showed that effective continuing education programs for healthcare providers must be built on solid field data. This is to ensure that evidence-based clinical practice guidelines are continually improved for tactical combat casualty care (Lairet et al., 2012).

As computerized technology has become increasingly smaller and more sophisticated, wireless interfaces can now be easily included on miniature devices. These wireless solutions could be used in documenting health information on our military personnel. Moreover, this can help to achieve better health outcomes from injuries that were sustained in a tactical environment. Strategically, such information can also provide predictive health demand signals to inform policy as well as facilitate informed healthcare resource acquisition strategies. Pursuing such a strategy can ensure that military personnel would have the right kind of medical infrastructure at the right time, and thereby prevent health issues from becoming health epidemics.

E. RESEARCH QUESTIONS

1. Which classes of devices/sensors are most appropriate for a tactical environment?
2. What is a reachback method for making patient information available to medical providers in intermediate and ultimate treatment facilities?

To answer the first question, authors will explore factors that should be considered during a selection process of sensors for personnel in a tactical environment.

To answer the second question, authors will perform a review of existing studies and conduct experiments with available sensors. Based on this review, the authors will determine the best available method of transmitting sensor data to medical providers in a tactical environment and on to higher echelons of care.

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II. PRIOR RESEARCH AND RESEARCH DESIGN

A. RESEARCH METHODOLOGY

To answer the research questions, the authors have selected a mixed method research approach. A qualitative approach is required to identify appropriate sensors for a tactical environment as well as gain familiarity with networking and reachback capabilities in a maritime environment. Furthermore, qualitative research is necessary to identify specific performance requirements of technologies selected for experimentation and evaluation.

During the quantitative portion of this work, the researchers will examine the data gathered during experiments. Specifically, the researchers will evaluate sensor effectiveness and reachback capability during data transmission from the point of collection to the ultimate destination.

B. EVALUATION FRAMEWORK

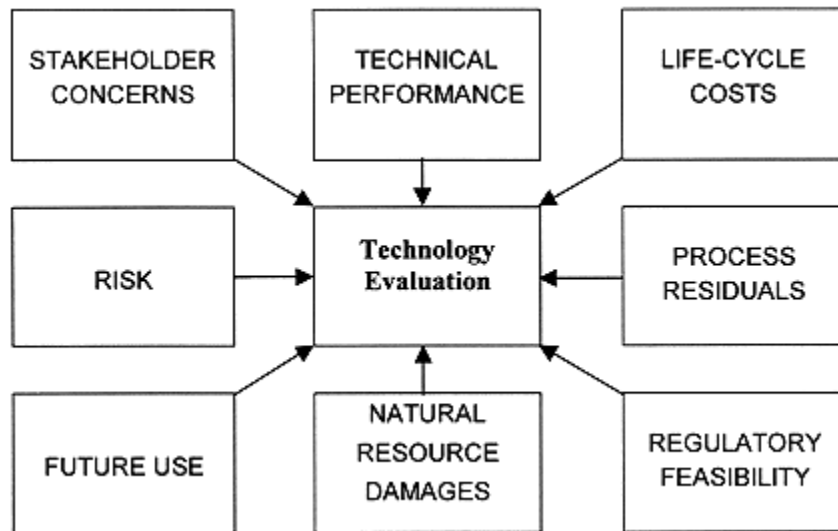
When considering the breadth and depth of the presented research problems, the authors determined that there is no single best model, theory, or framework that can address the problem space for health monitoring system evaluation. Consequently, the authors developed their own framework that leverages the frameworks of other researchers from the health and information system domains.

Information systems (IS) and technology (IT) solutions in healthcare incorporate a social aspect as well as technological aspect (Muhammad, Teoh & Wickramasinghe; 2013). There are many variants of IS socio-technical evaluation frameworks (Bostrom & Heinen, 1977; Walsh & Ungson, 1991; Hartwick & Barki, 1994; Levy & Green, 2007; Holden & Karsh, 2009; Yusof & Yusuff, 2013). However, there is not one single framework that fits within parameters of Defense Health. The Defense Health Agency's guiding objective is the Quadruple Aim of increased readiness, better health, better care, and lower cost for delivering health services (Middleton & Dinneen, 2011; Military Health

System, 2014). Due to the complexity among information systems, technological solutions, and the provisioning of healthcare, it was critical to develop a multi-faceted approach. This approach evaluates a Defense Health IT system through three main lenses: technology, system users, and organization as a whole. The authors developed an IS evaluation framework applicable to the DHA environment that is based on organizational objectives and blends concepts from two existing IS evaluation frameworks: the Integrated Technology Evaluation Framework (ITEF) and the Human, Organization, and Technology-Fit (HOT-Fit) Framework.

The Center for Environmental Restoration Systems (CERE) utilized ITEF to select treatment and containment technologies for remediation of contamination problems at the United States Department of Energy sites, DOD facilities, and private industry (Regens et al. 1999). As shown in Figure 3, the technology evaluation framework used by CERE incorporates eight criteria.

Figure 3. CERE technology evaluation framework criteria

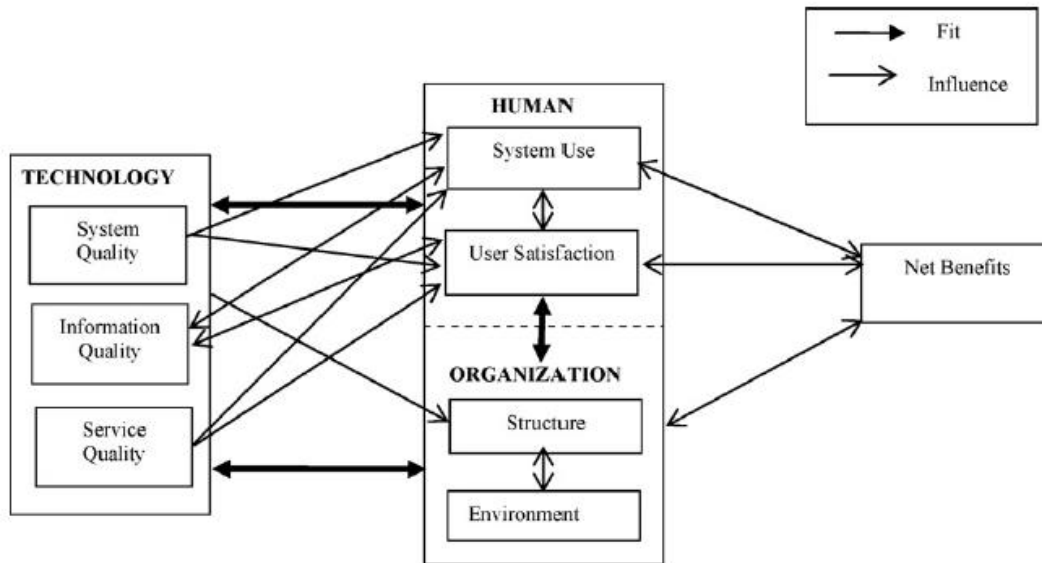


Source: Regens, J. L., et al. (1999) Integrated framework for assessment of site remediation options. *Federal Facilities Environmental Journal*, 10(1), 85.

The Human, Organization, and Technology-Fit evaluation framework (Figure 4) is the product of combining specific evaluation factors and dimensions

from the IS Success Model and the IT-Organization Fit Model (Yusof, Kuljis, Papazafeiropoulou, & Stergioulas, 2008). Yusof and colleagues (2008) concluded that the HOT-Fit evaluation framework is valuable for any health information system.

Figure 4. Human, Organization, Technology-Fit framework



Source: Yusof, M. M., Kuljis, J., Papazafeiropoulou, A., & Stergioulas, L. K. (2008). An evaluation framework for Health Information Systems: human, organization and technology-fit factors (HOT-fit). *International Journal of Medical Informatics*, 77(6), 386–398.

The authors combined the eight evaluation criteria from CERE with the three HOT-Fit dimensions. They then applied the dimensions and criteria to the Defense Health objectives and developed the Objectives Based Health Information Technology (OBHIT) Evaluation Framework (Figure 5).

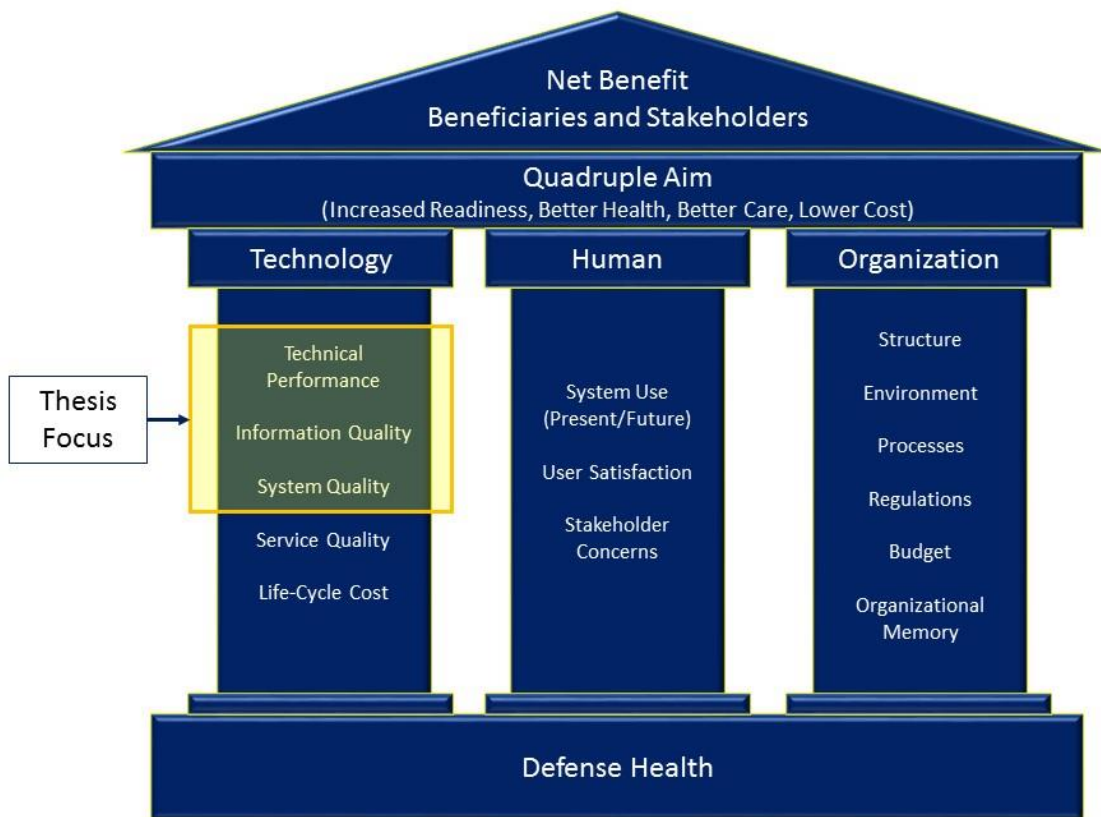
The scope of this thesis is on the Technology pillar, specifically on the technical performance, information quality, and system quality dimensions. The technical performance evaluates the effectiveness, readiness, implementability, and reliability of the sensor system. The researchers will use information quality to investigate the relevance of the sensor data for the medical community. Furthermore, the researchers will examine the system quality by analyzing data

utility and data accuracy. The other two factors of the OBHIT evaluation framework dimension address

- Service quality, which addresses the support post-implementation
- Life-cycle cost, which addresses costs of implementation and support as well as return on investment for such solutions

These two factors are not within the scope of this thesis.

Figure 5. Objectives Based Health Information Technology evaluation framework



C. RESEARCH SCOPE

This research is based on previous work conducted by Miles (2012) and Bordetsky (2015). Miles (2012) demonstrated the need for service members in a tactical environment to be outfitted with biomedical sensors. This effort was

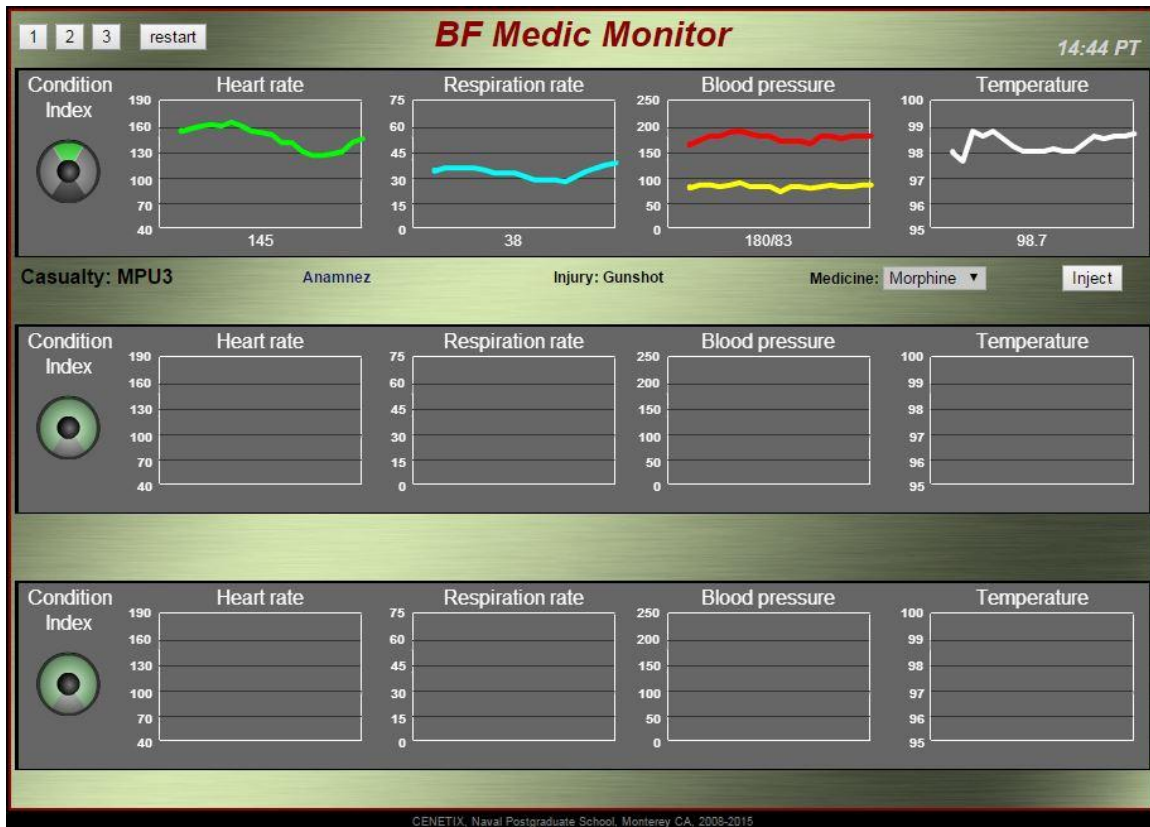
conceptual in nature and did not include a proof-of-concept. Bordetsky (2015) and a Naval Postgraduate School (NPS) Center for Network Innovation and Experimentation (CENETIX) team on the other hand were able to demonstrate reachback capabilities in a simulated environment. However, data in those experiments were randomly generated by a computer program that was visualized in a simulated health status record, the CENETIX Observer Notepad (Figure 6) and the CENETIX Battlefield Medical Medic Monitor (Figure 7). In addition, the NPS team tested the sensor functionality in a non-maritime environment where open spaces may not pose many line of sight (LOS) issues for a successful demonstration of reachback capabilities. Furthermore, actual biomedical sensors have not been tested. Finally, additional testing is required in a maritime environment where reachback capabilities may be strained due to vessel structures, distance to access points and antennas, as well as natural interferences.

Figure 6. CENETIX Observer's Notepad

Date and Time (Zulu)	Comments	Attachment	Delete
6/3/2015 21:40:06	BFMedic Console: Casualty detected (ID=61).		
6/3/2015 21:40:00	BFMedic Console: Casualty detected (ID=62).		
6/3/2015 21:39:55	BFMedic Console: Casualty detected (ID=61).		
6/3/2015 18:20:05	BFMedic Console: Casualty detected (ID=61).		
6/2/2015 09:50:29	BFMedic Console: Medicine injected (for causlaty ID=).		

Source: CENETIX Resource Portal. (n.d.). Screenshot of the observer's notepad. Retrieved from: <http://cenetix.nps.edu/cenetix/Resources.asp>

Figure 7. CENETIX Battlefield Medical Medic Monitor system



Source: CENETIX Resource Portal. (n.d.). Screenshot of BF Medic Monitor. Retrieved from: <http://cenetix.nps.edu/cenetix/Resources.asp>

1. In Scope

Based on the authors' OBHIT evaluation framework, this thesis focuses on technical performance (effectiveness, readiness, implementability, and reliability), information quality (data relevance), and system quality (data accuracy) of the sensor network within a maritime environment, specifically limited to Visit, Boarding, Search and Seizure (VBSS) operations (Table 1).

Table 1. Evaluation criteria for sensors in a maritime environment

Dimension	Factor	Description
Technical Performance	Effectiveness	Is the overall system able to meet the requirements of transmitting sensor data to a medical facility in near real time?
	Readiness	How difficult is it to deploy the sensor system in a maritime environment?
	Implementability	What is the impact of implementing the sensor system in a maritime environment on stakeholders?
	Reliability	Can the sensor system remain operational for the duration of required mission?
Information Quality	Data relevance	Is the sensor data relevant to medical providers?
System Quality	Data accuracy	Is the data transmitted to medical providers accurate?

As presented in Figures 8 and 9, there are three major network segments. These are the Body Area Network (Figure 8), the mobile tactical network (Figures 8 and 9), and the reachback network to the Military Health System (MHS) Data Repository (MDR) (Figure 9). The scope, set by the authors, is to test whether NPS-acquired biomedical sensors would serve as viable candidates for field-testing and integration into the Maritime Interdiction Operations (MIO) environment and as a proof-case for a more global strategic integration into Defense Health.

Figure 8. A VBSS boarding team member equipped with system of biomedical sensors and a mobile computing device

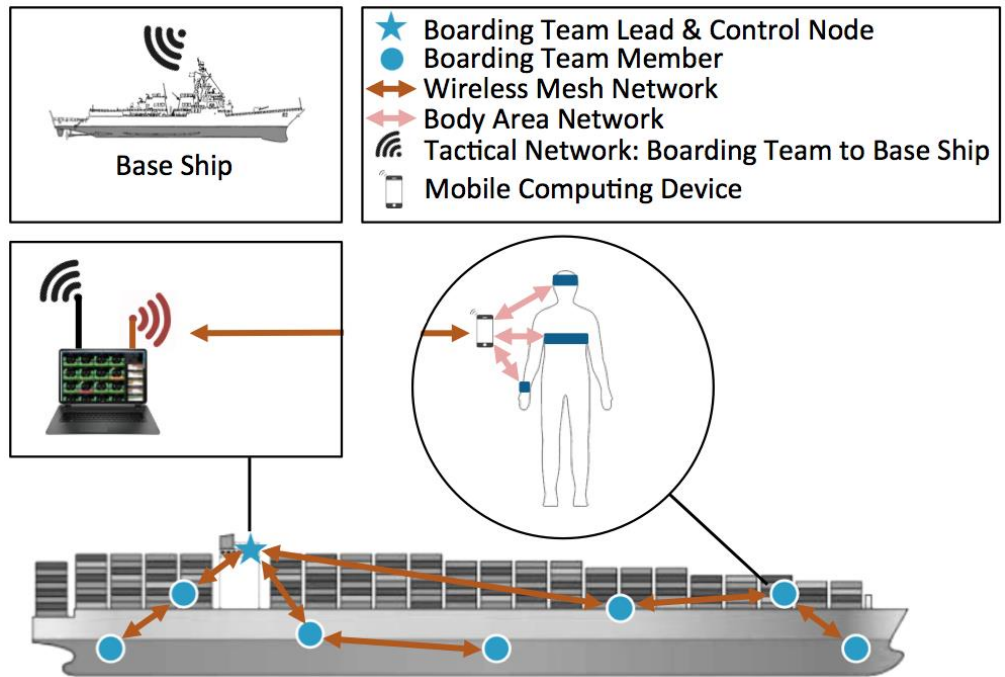
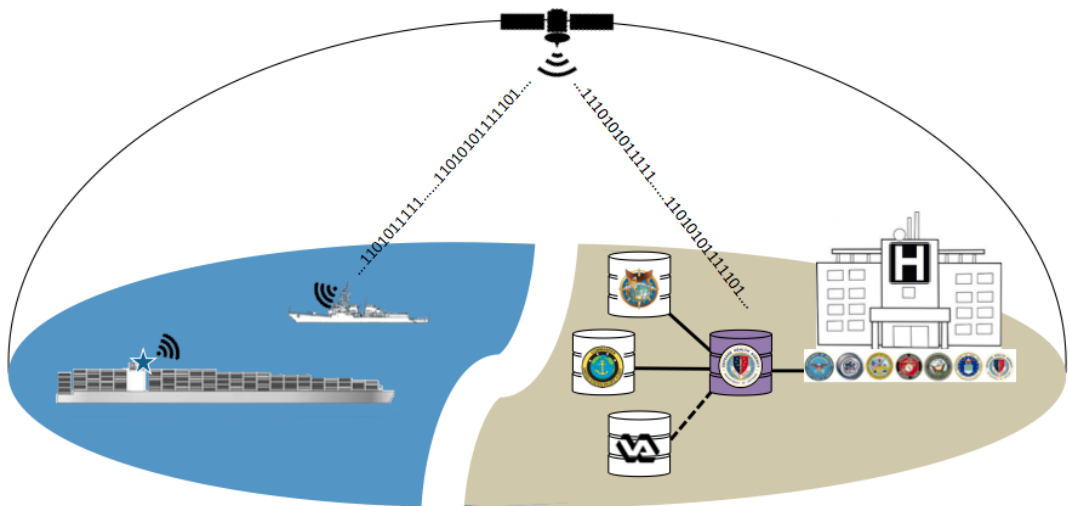


Figure 9. A VBSS boarding team on post Panamax container ship transmitting data from the control node to the MDR via a base ship



The authors will conduct experiments within the constraints of the down-selected equipment and environment. Equipment utilized for the purpose of this research work includes wireless sensors, manufacturers' proprietary system applications and hardware, laptops, mobile computing devices, and wireless mesh radios. A summary table and list of equipment is provided in Appendix B.

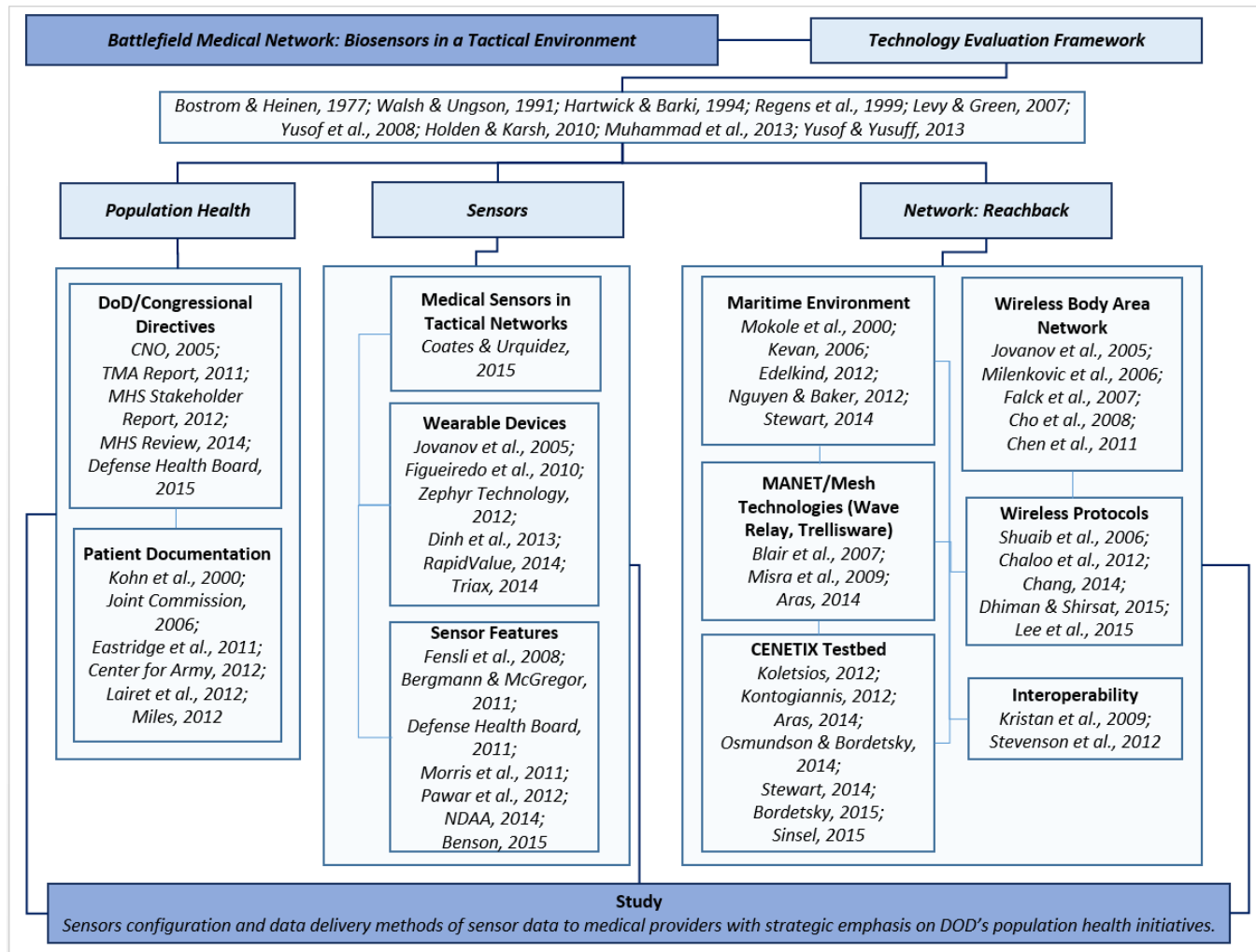
2. Omission

Researchers will test a sensor network and reachback capabilities within parameters of a near-realistic environment. This work does not detail individual protocols. It is assumed that the readers are already familiar with common network protocols. Instead, based on literature review and experiments, this work will provide recommendations for a best combination of technologies and network configurations for sensor implementation. Furthermore, researchers will not evaluate the validity or veracity of the sensor data, but strictly the availability of sensor data to medical providers.

D. LITERATURE REVIEW

Figure 10 depicts a literature map (the map) that organizes prior research reviewed by the authors. The map demonstrates how this research is organized into the three main areas: understanding prior research and the DOD policies as they pertain to population health; identifying the type of sensors feasible to capture and transmit patient health data; and identifying the best reachback methods for sensor data transmission from a maritime environment to a medical network operations center.

Figure 10. Literature map



Note: This literature map references reviewed works using an author-date format. The complete source information is provided in the List of References.

1. Prior Work Pertaining to Patient Health

Previous research identified gaps in patient care due to issues associated with patient handoffs and limited patients' medical information available to medical providers upon receipt of a patient (Defense Health Board, 2015). In addition, two initiatives have been implemented to improve patient handoffs. The first initiative is the 1997 congressional mandate for the DOD to have a means to track the longitudinal health of service men and women (National Defense Authorization Act, 1997). Then, in 2006, The Joint Commission initiated a patient hand-off requirement with "the primary objective of a hand off is to provide accurate information about a [patient's] care, treatment, and services, current condition and any recent or anticipated changes ... in order to meet [patient] safety goals" (Patton, 2007, p. 5).

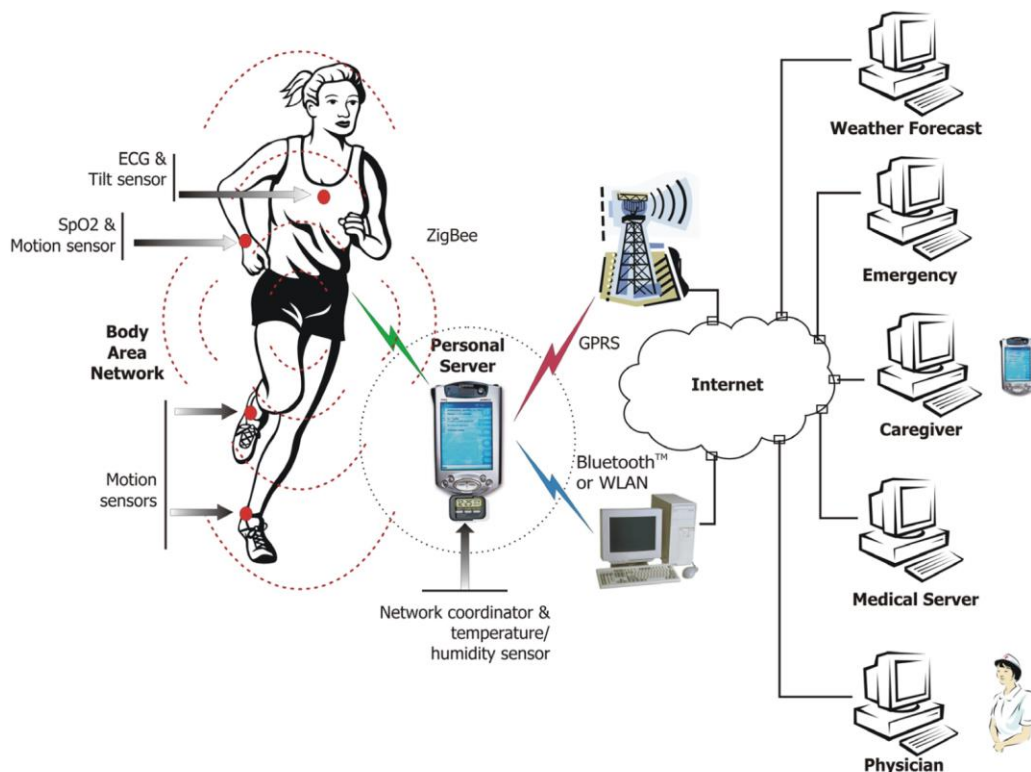
Miles (2012) proposed establishment of the Casualty Network System (CNS) utilizing a tactical ad-hoc mobile network framework where medical information, such as vital signs and injury information, would be transmitted wirelessly from individual biometric devices into medical health systems via tactical radios and or standalone devices. While a group of researchers at the Naval Postgraduate School stood up a testbed for ongoing experiments of parts of the CNS, the CNS system has not been developed in its entirety or tested in actual tactical environment under realistic operational conditions (Miles, 2012).

In research conducted by Coates and Urquidez (2015), a common theme was discovered in the documentation of vital signs: "the need to discover a wireless automatic solution to remedy deficiencies in historical monitoring and recording methods." (p. 22). Their research further refined technological sensor design requirements that would facilitate the implementation of a wide body area network, which include integration, power-source miniaturization, and reliability.

Jovanov and colleagues (2005) discussed the integration of wearable devices as part of a telemedicine system. They argued that the use of these devices can result in the "early detection of abnormal conditions and prevention

of its serious consequences” (p. 1). In the research, they leveraged the concept of a body area network (BAN) or personal area network (PAN), wherein an individual is equipped with multiple sensors. Figure 11 presents the concept of multiple body sensors that communicate with a personal server. This personal server then retransmits data via a wireless medium to various servers on the Internet.

Figure 11. Wireless Body Area Network of intelligent sensors for patient monitoring



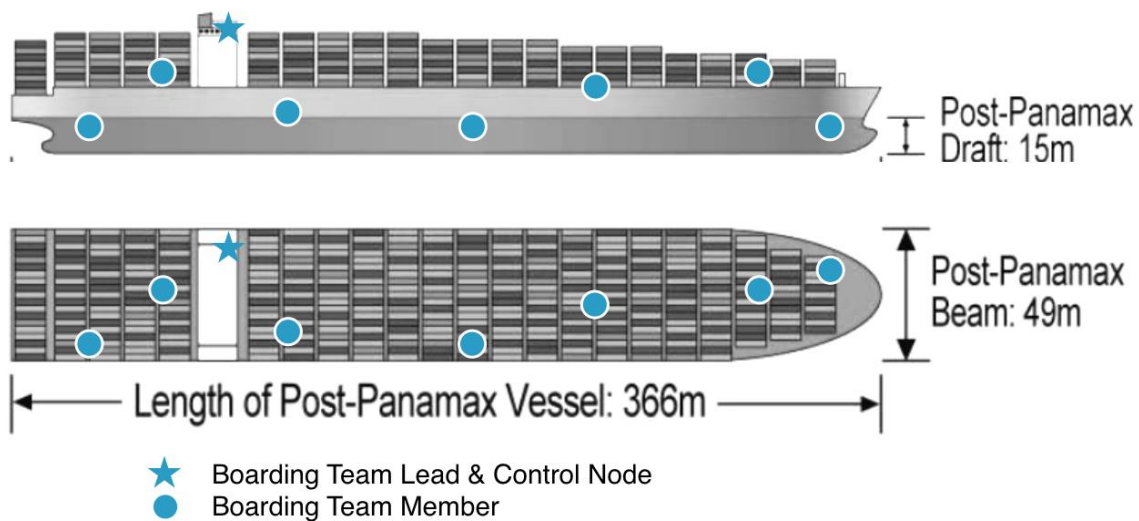
Source: Jovanov, E., Milenkovic, A., Otto, C., & De Groen, P. C. (2005). A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation. *Journal of Neuro Engineering and Rehabilitation*, 2(1), 6.

2. Tactical Environment

As previously introduced, the scope of this research is within the confines of a maritime environment, specifically, for the use in MIO, such as during VBSS operations. Figure 12 provides a visual snapshot of boarding team location

during the infiltration phase of a VBSS. An eight-person team typically would board a Vessel of Interest (VOI) and establish team Command and Control (C2) in the vessel's pilot house (Nguyen & Baker, 2012). In this environment, it is conceived that each boarding team member (BTM) would be equipped with one or multiple biomedical sensors that transmit collected data to a tactical or medical operations center (TOC/MOC) (Figure 8). It is within the TOC/MOC where a tactical medical advisor would provide C2 support recommendations to tactical leaders.

Figure 12. Boarding team during a VBSS infiltration phase on a post Panamax vessel



Adapted from: Panama Canal Authority. (2006). *Proposal for the expansion of the Panama Canal: Third Set of Locks Project*. Retrieved from <http://www.panacanal.com/eng/plan/documentos/propuesta/acp-expansion-proposal.pdf>

Unlike signal propagation issues that impact wireless fidelity in hospitals, urban areas or on open ground terrain, the shipboard environment presents its own set of unique challenges. These include steel bulkheads, metal machinery, and ship-based wireless interference. All of these degrade and contend with signals from boarding team members (Mokole, Parent, Samaddar, Tomas, & Gold, 2000; Kevan, 2006; Stewart, 2014). This issue must therefore be mitigated by including a means for biomedical sensors to leverage current mobile ad-hoc

network technologies, such as virtual extension (VE) mesh nodes and WaveRelay or TrellisWare radios to establish data reachback to the central node.

In addition, compounding communications issues on board the VOI is the base ship reachback radio networking. Under normal circumstances, the base ship will be within LOS of the boarded VOI, thereby assuring a permissive environment for tactical network radio systems currently employed on surface ships. However, there are times when base ships will stay beyond the horizon. This predicates the use of tactical satellite communication or similar relay links to facilitate a sustained situational awareness in the TOC onboard the base ship (Edelkind, 2012).

While neither of these major networking issues is within the scope of this research, they are germane to understanding environment and their impact on operations. For the purposes of this work, the researchers presume that boarding team (BT) to base ship communications are established and that uplink bandwidth is sufficient to support regular network traffic.

3. Physiological Telemetry

The concept of physiological telemetry is not a novel idea stemming from the ubiquity of smart devices and internetworked individuals. Rather, the concept dates back to 1924, with a cover story that introduced the idea of a radio doctor who could remotely diagnose and send prescriptions to patients (Radio News, 1924).

Technology was not quite sophisticated enough to make the radio doctor a reality in the first half of the 20th century. However, progress continued, and in less than 25 years later, one of the first cornerstones was set in place to make the radio doctor a reality. The advent of the Holter monitor, developed in 1947, provided cardiologists with an opportunity to remotely record heart measurements (National Museum of American History, 2011). This advent gave rise to physiological telemetry, the cornerstone for remote medicine.

Today, telemedicine has become common place, creating force-enabling opportunities for Defense Health. This capability is predicated on having the right technologies in place that create the infrastructure for remote medicine. One major component is physiological telemetry and the ability for a health practitioner to remotely keep a proverbial pulse check on the health status of their patients.

Within the context of this research and in line with the authors' framework, physiological telemetry must provide data that are reliable (effectiveness factor), actionable (relevance factor) and accurate (accuracy factor). All of these factors are critical to ensuring that remote medical management and tactical decision support are positively executed. The subsections that follow provide biomedical sensor-specific details that should be considered as part of a selection criteria.

(1) Deliberate Omission

One additional factor not captured within the OBHIT evaluation framework is timeliness and the near-real time transmission of health data. When considering the tactical environment and the limitations imposed by network constrained environments such as in MIO, the authors contend that not all factors can be assured nor given equal importance. It is asserted that, within certain prescribed medical practice limitations, timeliness is the only factor that can afford the highest degree of variability. Therefore, the authors submit that reliability, actionability, and accuracy must be assured at the expense of timeliness. This assertion is made based on current medical practice that prescribes patient assessment frequency to a rate of one assessment per 15 minutes (Miltner, Johnson & Deierhoi, 2014; Center for Army Lessons Learned, 2012; Schulman & Staul, 2010).

Consequently, the authors have excluded this factor for direct assessment in their research. However, the authors concede that timeliness is nonetheless worth investigating and will include it as part of sensor testing and analysis where appropriate.

b. Key Tactical and Population Health Measurements

Key health metrics and measurements diverge in the information and actionability they offer between healthcare providers in tactical settings and those for longitudinal population health monitoring. In the tactical setting, it is critical for a healthcare provider to obtain key prehospital data to make appropriate and immediate triage and treatment decisions (Miles, 2012; Dinh et al., 2013). Such data include heart rate, respiration rate, systolic blood pressure, body temperature and Glasgow Coma Scale (Dinh et al., 2013; Coates & Urquidez, 2015). While these data may offer longitudinal insight, additional measurements can prove essential to better understanding and predicting population health. Lacking knowledge of future demands intuitively translates to “we do not know what we need until we need it” (San Francisco Unified School District, 2009). Therefore, it is difficult for health system planners to target key population health measurements until an increase of morbidities have become epidemic in nature. Based on our most recent conflicts in Afghanistan and Iraq, Defense Health has become more attuned to two specific morbidities. These are concussive force from exposure to explosions and personal air quality due to exposure to burn pits.

Concussive impact: By 2010 Defense Health saw a 280% increase in annual mild traumatic brain injuries (mTBI) over the 2000 baseline (Defense Health Board, 2011). This increase is mainly attributed to injuries sustained by explosions, as indicated by a two-year review of the JTTR (Laird et al., 2011). Currently, the main means of measuring the effects of concussive forces is through the administration of the Automated Neuropsychological Assessment Metrics (ANAM) tool, which gives healthcare providers insight into the potential effect of an impact by comparing an individual’s pre-deployment score to a post-injury score (Defense Health Board, 2011). This tool, however, has proven to be inadequate for diagnosing individuals or at facilitating return-to-duty decisions (Defense Health Board, 2011). Consequently, having an ability to unobtrusively and persistently measure concussive forces from a blast could help inform

healthcare providers of impact nature as well as support in developing better-informed diagnosis profiles for traumatic brain injury (TBI). More importantly, by having a means to continuously monitor the number of concussive incidents and feed the concussive incidents data to health systems planners, it is possible to better build capacity for mTBI treatment needs in garrison and within the VHA.

Personal air quality: The pulmonary risks of burn pits came to national attention in 2010 with a release of several media stories (Morris, Zacher & Jackson, 2011). In response to the increased incidence of respiratory illnesses associated with burn pits from Iraq and Afghanistan, Congress included language in the 2014 National Defense Authorization Act to forbid the burning of specific materials that have attributed to poor air quality and affected Defense personnel (Public Law, 113–66, 2013). Similar to dosimetry badges worn by radiology personnel, having a means to measure air quality for individuals can provide an exposure specificity that can better inform tactical decision makers on when to impose temporal exposure limitations. Additionally, such data can epidemiologically serve as prospective health information, should future health complications arise among exposed individuals.

c. *Wireless Health Monitoring*

The concept of an Internet connected Wearable Wireless Body Area Network (WWBAN) was developed by Milenkovic and colleagues (2006). This concept proposed the possibility of deploying an array of sensors onto individuals who were connected to a personal server that was either carried by the individual (e.g., cell phone) or located in the immediate vicinity (e.g., laptop). Such a capability could provide the user with physiological feedback information as well as create a continuous data source that could be merged with the individual's health record. Ultimately, this proposition would better empower the user as well as their health care team towards improved health.

This proposed concept is predicated on a system of sensors that works in harmony with a control node, the personal server, which directs nodal

synchronization as well as provides for the collation of data (Milenkovic, Otto & Jovanov, 2006). Moreover, the ability to leverage a personal server capability would ensure that the collated data would then be transmitted onto a health system server. Ultimately, this data would become a part of the individual's health record (Milenkovic et al., 2006)

d. *Sensor Connectivity*

In advance of presenting unobtrusive wearable sensor technologies that are currently available on the market, it is critical to first discuss the means through which such sensors should be connected to the Department of Defense Information Network. There are currently three main means for sensors to connect to a computing device. These are wire to sensor, closed source wireless connection, and open source wireless connection.

Wire to sensor: Such a method requires the sensor to be physically attached to a computing device via a cable. Data are then transmitted from the sensor's onboard memory. This means is the least sophisticated and allows for the lowest amount of flexibility, modularity, and scalability (Milenkovic et al., 2006). While this means of data collection in healthcare has been practiced as early as 1947 with the advent of Holter monitors and has had a proven record of medical efficacy, it is also limiting in that collected data are usually analyzed offline and hours or days after measurements have taken place (National Museum of American History, 2011).

Closed source wireless connection: This method provides for a solution that is generally vendor specific and precludes or limits the introduction of third party nodes onto the same wireless connection. Generally, such a solution requires the use of a proprietary sensor receiver that is attached to a computing device and facilitates receipt of data. This means of connecting the sensor can have a high degree of sophistication, but confines the user to a single vendor solution that may require additional sensors for the monitoring of other physiological measurements.

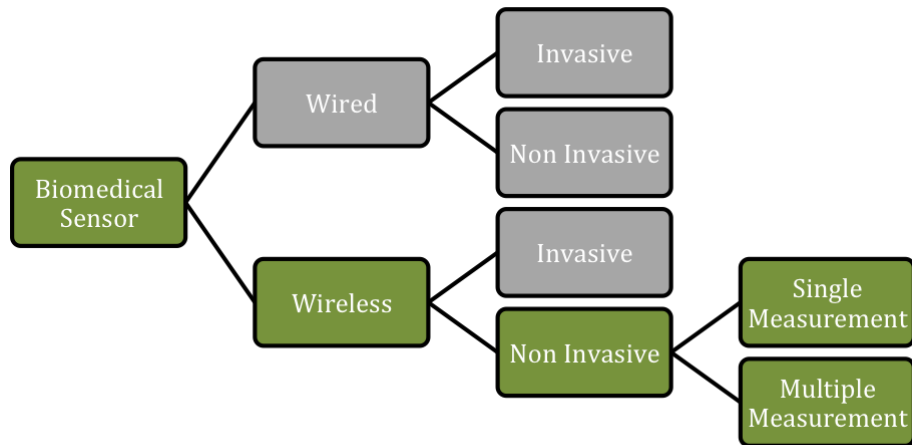
Open source wireless connection: In this method, nodes adhere to widely accepted standards such as ZigBee or Bluetooth standard. The use of nodes or devices leveraging such a wireless connection allows for the highest degree of flexibility, modularity, and scalability as a single standard wireless protocol can permit a computing device to connect to multiple sensor nodes without requiring multiple antennae or cards on the computing device.

e. *Classes of Sensors*

To better understand what is meant by biomedical sensors, it is best to baseline an interpretation of its meaning. In the context of biotechnology and medicine, the National Institute of Health defines the term as “sensors [that] are tools that detect specific biological, chemical, or physical processes and then transmit or report this data. Some sensors work outside the body while others are designed to be implanted within the body” (National Institute of Health, n.d.).

When conducting an environmental scan of currently available sensors, the researchers opted to forego the traditional search methodology generally used in the biomedical sciences. The researchers acknowledge that methodical searches on research sites using inclusion and exclusion criteria are preferred. However, it was determined that a current state sensor survey would be obsolete before publication due to the velocity in which wireless sensors are being introduced into the market (RapidValue, 2014). Consequently, the researchers selected a method to classify sensors currently available as presented in Figure 13. An example of each class or sub-class that has been considered for research within the scope of this work is included in this section.

Figure 13. Classification mapping of biomedical sensors



The researchers deselected invasive sensors from their evaluation given the research constraints of not having the capability to examine invasive sensors in planned experiments. This decision was furthermore influenced by the fact that non-invasive sensors currently hold a higher acceptance rate than implantable sensors for individuals without chronic morbidities (Darwish & Hassanien, 2011). Therefore, any potential introduction of biomedical sensors into a DOD tactical environment must consider acceptance criteria to ensure that users would adopt and comply with their use in the field.

In addition to deselection of invasive sensors, the researchers also deselected wired sensors. This decision was based on an important consideration for personnel operating in a tactical environment where wireless sensors would be most permissive in allowing users to exercise the maximum range of motion.

Wireless non-invasive sensors are currently the most widely used in the marketplace with an expected reach of just over 170 million online by 2016 (Wipro Insights, 2013). Unlike the classes of sensors excluded from this research, this class of sensors can be directly marketed and sold to the end-consumer.

As graphically presented in Figure 13, this class has also been further subdivided into two subclasses. The subclasses demark whether a sensor is capable of conducting single or multiple biosignal measurements.

Single measurement wireless non-invasive sensors (Figure 14) collect data on one specific physiological measurement. Conversely, multiple measurement sensors (Figure 15) can collect and transmit data on more than one health measurement. The most widely implemented type of sensor that falls into the single measurement sub-class are chest strap or wrist-wearable heart rate monitors. These sensors can connect wirelessly to either an associated watch, fitness machine (e.g., treadmill), or mobile computing device. Similarly designed multi-physiological measurement sensors currently comprise the market space and offer more tactically relevant data for monitoring operator health statistics.

Figure 14. Example of a heart rate monitor connected to a smartphone via Bluetooth



Source: Wahoo Fitness, n.d. BlueHR. In *Wahoo*. Retrieved February 1, 2016, from http://www.wahoofitness.com/media/wysiwyg/cms/Wahoo_BlueHR_with_iPhone.jpg

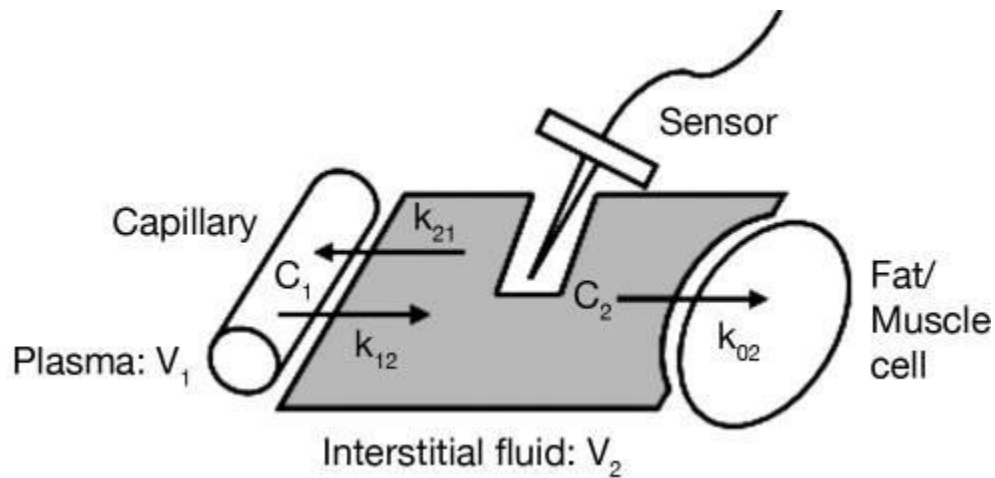
Figure 15. Example of a headband sensor that can measure heart rate and body temperature



Source: Spree Wearables, n.d. Spree Wearables, Inc. In *Fundable*. Retrieved February 1, 2016, from <https://www.fundable.com/spree>

Wired invasive sensors are considered sensors that are connected at the physical layer to a computing or radio device. The most predominantly type of this sensor currently used in the market are continuous glucose monitoring devices. In Figures 16 and 17, it can be seen that the sensor actually penetrates the wearer's skin, where the sensor then collects interstitial fluid glucose concentration.

Figure 16. Glucose wired sensor inserted into skin



Source: Keenan, D. B., Mastrototaro, J. J., Voskanyan, G., & Steil, G. M. (2009). Delays in minimally invasive continuous glucose monitoring devices: a review of current technology. *Journal of Diabetes Science and Technology*, 3(5), 1207–1214.

Figure 17. Invasive glucose monitor



Source: Medtronic, n.d. Continuous Glucose Monitoring. In *Medtronic*. Retrieved February 1, 2016 from <http://www.medtronicdiabetes.com/products/continuous-glucose-monitoring>

Wired non-invasive sensors are those that collect health measurements from the patient using skin adhesive sensors and transmit the data to a recorder, computing device, or radio. The Holter monitor (Figure 18) used to monitor electro-cardio activity most typifies this class of biomedical sensor in healthcare.

Figure 18. Holter monitor: non-invasive sensor example



Source: Montgomery Cardiovascular Associates, 2016. Retrieved February 1, 2016 from <http://www.montgomerycardiovascular.com/innovative-procedures/holter-monitoring/>

Wireless invasive sensors (Figure 19) are considered sensors that are implanted into an individual where they can reside for months, years, or even a lifetime and then communicate measurements wirelessly to a computing device. The first Food and Drug Administration (2014) approved device that fell into this category is a sensor that used in managing individuals who have a history of heart failure.

Figure 19. Wireless invasive sensor



Source: Abington–Jefferson Health, 2016. *Abington hospital cardiologists implant new device to monitor patients with heart failure.* Retrieved February 1, 2016, from <http://www.abingtonhealth.org/news/2016/wireless-monitoring-sensor/#.VrQI5DYrJhE>

f. Sensor Selection Criteria

The selection criteria are based on best practice recommendations from other researchers derived from the literature review. Also included here are criteria that are critical to DOD due to the nature of its mission and the constraints placed on the acquisition process.

The selection criteria include cybersecurity, unobtrusiveness, wireless communication, and low power energy consumption. Additionally, sensors under considerations should be able to seamlessly fit into the mobile computing ecosystem prevalent in industry today (Figueiredo, Becher, Hoffmann & Mendes, 2010).

Cybersecurity: Security in the information domain is critical to ensuring that force-multiplying resources such as information systems do not become compromised. This includes the inadvertent revelation of presence through overt signal broadcasts, the ability for the adversary to inject malicious code (Benson, 2015), or providing the adversary with critical force data such as position location information that could be used for weapons with GPS targeting capabilities.

Unobtrusiveness: Warfighters in a tactical environment are usually outfitted with multiple layers of protective equipment and gear. Additional items must be lightweight and not compromise the integrity of protective clothing. Unobtrusiveness in this context also accounts for user comfort to ensure that both valid physiological measurements can be taken. User hygiene and acceptance factors also are accounted for in this context (Bergmann & McGregor, 2011; Fensli et al., 2008).

Wireless: Movement in a tactical environment must allow for an operator to exercise a high degree of range of motion. Biomedical sensors therefore should not be connected to a computing device via wires as this can affect the aforementioned as well as affect user-comfort (Pawar, Jones, Beijnum & Hermens, 2012; Figueiredo et al., 2010; Fensli, Pedersen, Gundersen & Hejlesen, 2008). Additionally, having the ability to leverage multiple or diverse

wireless protocols is important as it can create opportunities to conduct network management functions when indicated.

Low-power energy: Given certain tactical operating environments, operators may go for several hours or even days without having the ability to have battery-powered gear recharged. Therefore, biomedical sensors that are equipped on tactical operators must consume minimal energy to ensure that such sensors can endure an entire mission before being exchanged or recharged.

4. Sensor Network

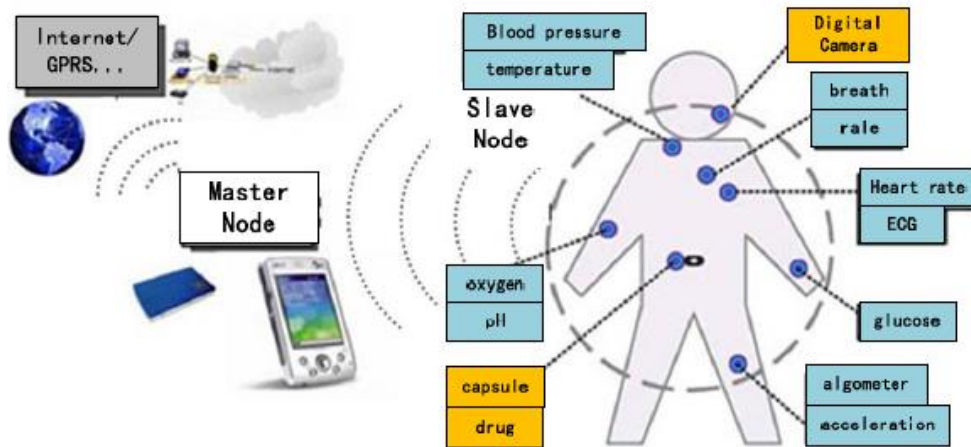
Several groups have researched and or prototyped Body Area Network (BAN) solutions. These solutions utilized either ZigBee (IEEE 802.15.4) or Bluetooth (IEEE 802.15.1) wireless communication standards for wireless sensor data transmission. The following are brief descriptions of some of the BAN solutions.

a. *Wireless Body Area / Sensor Network*

WSBN in a single-hop star network topology: In 2011, Chen and colleagues developed a prototype Wireless Body Sensor Network (WBSN) for a medical application consisting of four real-time high speed video streams and six low speed data sensors. This solution was based on ZigBee and a Single Carrier Ultra-Wideband (SC-UWB), because this solution, transmitting data and video, offers a higher data transfer rate than ZigBee or Bluetooth can provide by itself (Chen et al., 2011). This solution was based on a single-hop star topology (see Figure 11). It is composed of several sensor slave nodes and one master slave node (a PDA or a laptop or another hand-held device, Figure 20) that transmits data and video from slave nodes to a medical center database via Internet. The system has two modes, a low-speed mode and a high-speed mode. In a low speed mode, the ZigBee module acts as a control channel to conduct device discovery, initial connection, resource allocation, and low speed communication. The SC-UWB is active during a high speed mode, used to transmit large quantities of data. Chen and colleagues (2011) designed a new alternative media

access control layer (MAC) and physical layer (PHY) manager to allow system automatically switch between low-speed and high-speed transmission based on the data type.

Figure 20. WSN in a single hop star network topology

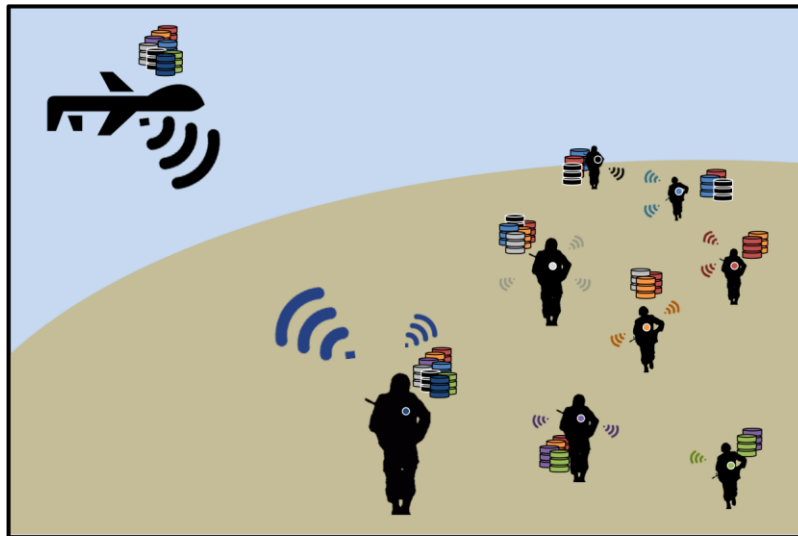


Source: Chen, X., Lu, X., Liu, Z., Fang, S., Jin, D., & Zeng, L. (2011, December). A heterogeneous high speed wireless body sensor network based on SC-UWB and ZIGBEE. In *2011 IEEE Global Telecommunications Conference (GLOBECOM 2011)*, (pp. 1–5).

Peer-to-Peer: Cho, Chang, Tsai, and Gerla (2008) proposed a Bluetooth Peer-to-Peer (P2P) network with unmanned aerial vehicles (UAVs). Under this scenario, every soldier would carry a personal digital assistant (PDA) and wear a bodysuit with multiple sensors that collect physiological measurements, such as heart rate and blood pressure. The bodysuit sensors transmit data via Bluetooth to the PDA, which acts as a mediator node. In this configuration, nodes, i.e., the PDAs, share any stored data with neighboring nodes. This data may only be data from the PDA's user or data that was acquired from multiple down streams, more distant users (Figure 21). The objective of this data-sharing scheme is to achieve a duplication of data across as many PDAs as possible. Ultimately, during periodic UAV flyovers, data would then be transmitted via 802.11g or WIMAX equivalent from the PDA that has aggregated the largest volume of health data, thereby reducing data synchronization from many PDAs to a single PDA.

Successful experiments in a simulated environment with controlled variables showed that this concept could work as proposed (Cho et al., 2008).

Figure 21. Simulation scenario setup for peer-to-peer sensor network

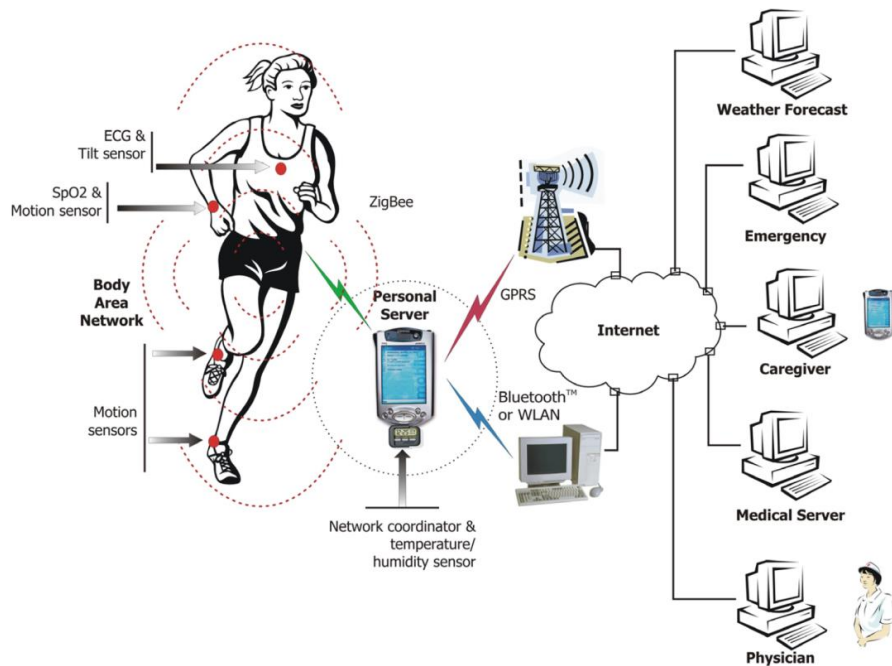


☰ Signifies the Warfighter's Health Data – Color Matched with their Biosensor

Patient Monitoring with ZigBee Wireless Body Area Network: In 2005, Jovanov and colleagues developed a conceptual prototype for a multi-tier telemedicine solution for patient monitoring during rehabilitation. In this model, a patient may be outfitted with a number of different sensors that communicate with a personal server via ZigBee. Figure 22 depicts the conceptual model of Jovanov and colleagues' WBAN solution. In their model, a personal server could be a PDA, a laptop, or a home computer.

Jovanov et al. (2005) decided to use the ZigBee wireless protocol because of its low-power requirement and the availability of a ZigBee compliant Telos sensor platform (see Appendix A). They further stated that ZigBee was chosen over Bluetooth for this telemedicine solution because Bluetooth wireless protocol is, “too complex, power demanding, and prone to interference by other devices operating in the same frequency range [which limits its] use for prolonged wearable monitoring” (Jovanov et al., 2005, p. 2).

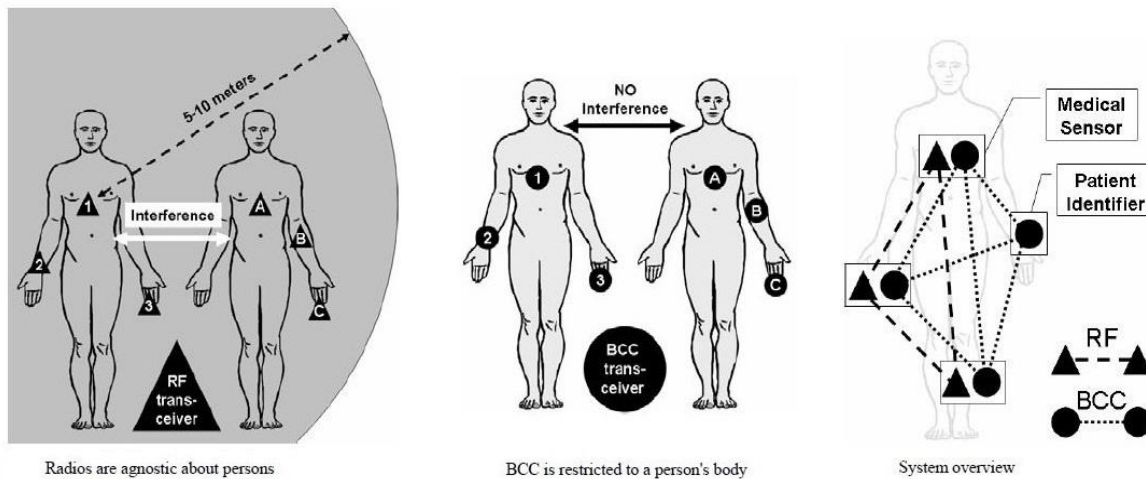
Figure 22. Wireless Body Area Network of intelligent sensors for patient monitoring



Source: Jovanov, E., Milenkovic, A., Otto, C., & De Groen, P. C. (2005). A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation. *Journal of Neuro Engineering and rehabilitation*, 2(1), 6.

Many sensors/Unique patient: In 2006, Falck, Baldus, Espina, and Klabunde proposed a distinctive plug and play Wireless Medical Body Sensors network utilizing a Body-Coupled Communication (BCC) where the attached sensors are coupled with a unique user or patient ID. The purpose of such a solution is to avoid sensor data from one patient being recorded in another patient's EHR. In this solution, the human body is used as a signal transmission medium. Figure 23 depicts the BCC solution as a plug and play WMBSN.

Figure 23. Body-Coupled Communication system overview



Source: Falck, T., Baldus, H., Espina, J., & Klabunde, K. (2007). Plug'n play simplicity for wireless medical body sensors. *Mobile Networks and Applications*, 12(2-3), 143–153.

b. Wireless Technologies: ZigBee versus Bluetooth

From the previous section, it is evident that some research groups preferred one IEEE standard to the other. However, the literature suggests that no one standard is better than any other standard. Selection of a wireless communication standard should depend on the application of the standard, the environment in which a solution would be deployed, and other organizational factors, such as a solution price and installation or configuration costs. (Lee, Dong, & Sun, 2015). Lee and colleagues (2015) discussed several studies that illustrated the applicability and performance capability of wireless standards in different environments. For example, in Baker's study of ZigBee's and Bluetooth's performance in industrial application it was found that "ZigBee over IEEE 802.15.4 protocol can meet a wider variety or real industrial needs than Bluetooth due to its long-term battery operation, greater useful range, flexibility in a number of dimensions and reliability of the mesh networking architecture." (Lee et al. 2015). However, in another wireless standard comparative study in the context of intra-vehicular communication, it showed that Bluetooth outperformed ZigBee in terms of power demand, bit rate, and latency (Lee et al. 2015). Table 2

provides a basic comparison between ZigBee and Bluetooth wireless communication standards.

Table 2. ZigBee and Bluetooth comparison

<i>Characteristic</i>	<i>ZigBee</i>	<i>Bluetooth</i>
Range	10-100 m	100 m
Data rate	20-250 Kbps	1 Mbps
Power profile	Years	Days
Operating frequency	868 MHz 902-928 MHz 2.4 GHz ISM	2.4 GHz ISM
Complexity	Simple	Complex
Network topology	Adhoc, star, mesh hybrid	Adhoc piconets
Number of devices per network	2 to 65,000	8

Source: Mulyadi, I. H., Supriyanto, E., Safri, N. M., & Satria, M. H. (2009, May). Wireless medical interface using ZigBee and Bluetooth technology. In *Third Asia International Conference on Modelling & Simulation, 2009. AMS'09*. (pp. 276–281).

In general, since ZigBee can operate either in a star or a peer-to-peer topology, ZigBee is better suited for applications with sensors and devices that require low data rate, long battery life, low user intervention and are deployed in a mobile network (Shuaib, Boulmalf, Sallabi, & Lakas, 2006). However, in 2010 the Bluetooth Special Interests Group (SIG) introduced the Bluetooth Low Energy (BLE) solution, which was implemented in Bluetooth 4.0 (Chang, 2014). BLE was enhanced to accommodate devices, such as wireless sensors, that require low power consumption and transmit little amounts of data. In addition, the BLE has two roles, a central and a peripheral role. A central role is responsible for managing multiple peripheral nodes simultaneously. The peripheral node is capable of connecting to several central nodes. As of 2014, the Bluetooth SIG was working on standardizing BLE for mesh networks (Chang, 2014). With this

improved master-slave node relationship and a BLE mesh network standard, Bluetooth may become an equal contender to ZigBee in a mobile ad hoc network.

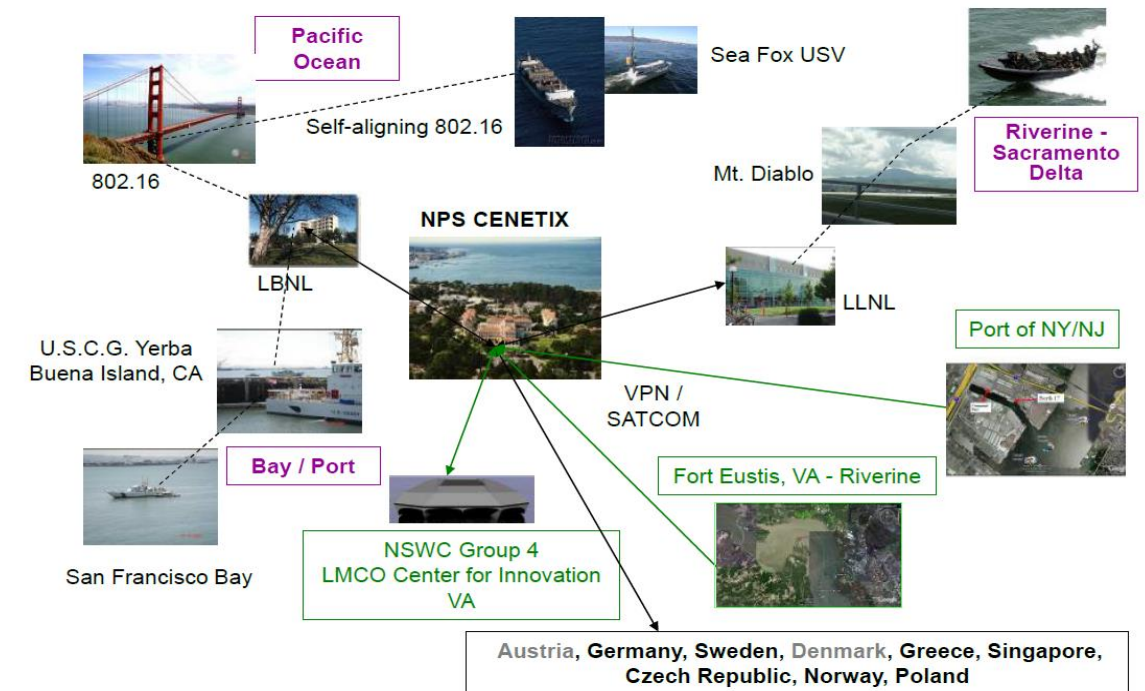
Regardless of which standard is utilized, there is a bigger challenge that becomes evident when ZigBee, Bluetooth, and Wi-Fi (IEEE 802.11) wireless standards are applied at close proximity or are collocated on the same device (Chaloo, Oladeinde, Yilmazer, Ozcelik, & Chaloo, 2012). All three co-exist in the same frequency band of 2.4GHz (Dhiman & Shirsat, 2015). Both, Bluetooth and ZigBee, have built in technologies that have little impact on Wi-Fi performance. However, Wi-Fi does not have the same cross-protocol interference controls (Chaloo et al., 2012). Dhiman and Shirsat (2015) demonstrated that when all three systems are deployed together, there is a significant reduction in throughput due to collision of data packets. If it is a system requirement to implement the three technologies simultaneously, the following should be considered during solution configuration and implementation phases:

- Adaptive frequency hopping (Chaloo et al., 2012)
- Sensor/device placement (Chaloo et al., 2012)
- Time scheduled data transmission (Dhiman & Shirsat, 2015)
- Channel sensing configuration (Dhiman & Shirsat, 2015)

5. Network Topology for a Maritime Environment

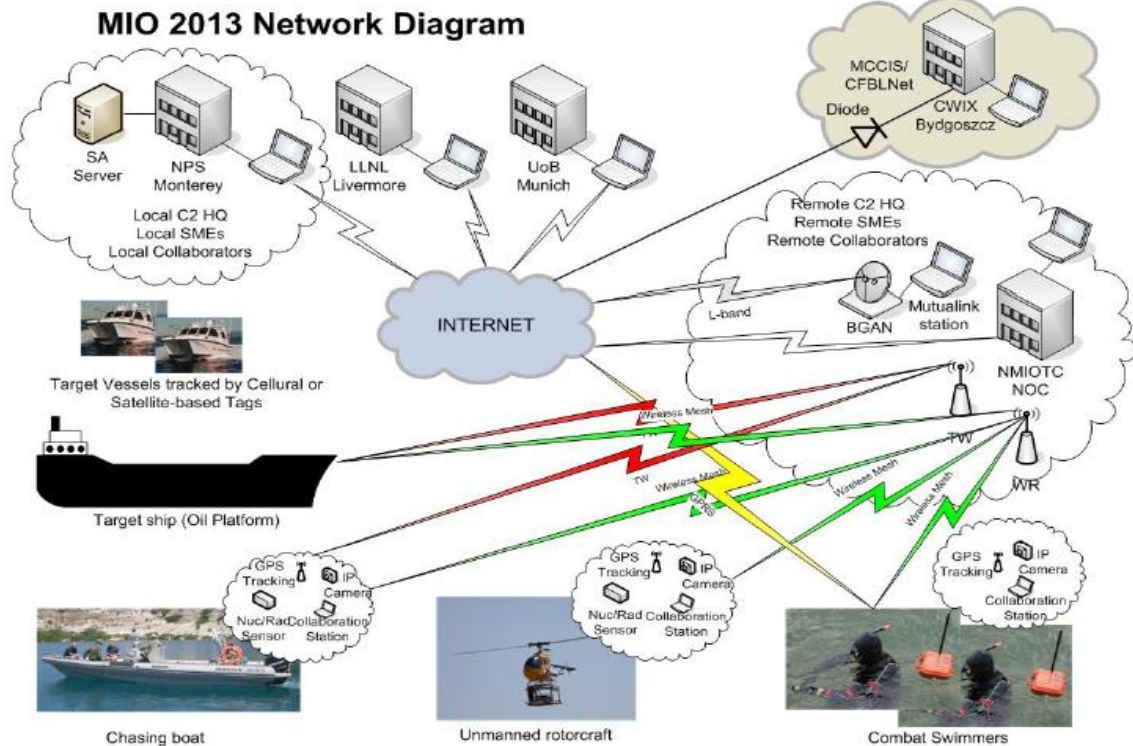
Previous research showed that wireless mesh and Mobile Ad-Hoc Networks (MANET) offer the best communications infrastructure for operations in a maritime shipboard environment. Research faculty and several NPS students have utilized the NPS CENETIX Tactical Network Topology (TNT) testbed (Figures 24 and 25) to conduct maritime experiment testing, specifically on tactical solutions for MIOs and VBSS operations. All of these solutions utilized either a mobile ad-hoc or a mesh MANET that were formed with WaveRelay, TrellisWare, virtual extension nodes, or a combination of these technologies (Aras, 2014).

Figure 24. CENETIX MIO testbed segment: San Francisco Bay, East Coast and overseas



Source: Bordetsky, A. (2015, April). *Maritime threat countering networking and collaboration testbed*. Personal Collection of Bordetsky, Naval Postgraduate School, Monterey, CA.

Figure 25. CENETIX MIO testbed tactical and reachback infrastructure



Source: Bordetsky, A. (2015, April). *Maritime threat countering networking and collaboration testbed*. Personal Collection of Bordetsky, Naval Postgraduate School, Monterey, CA.

a. Mesh and Mobile Ad Hoc Networks

A Wireless Mesh Network (WMN) is a network topology that has a hierarchical architecture composed of mesh clients, stationary mesh routers and Internet gateways. Mesh routers and Internet gateways comprise the mesh backbone of the WMN. Placement of MRs and IGWs is critical. Configuration of MRs and IGWs is subject to some constraints, such as environmental constraints, maximum number of channels, and the traffic demand. Some may say that WMN has a more reliable architecture as it takes fault-tolerance into consideration in case of link failures (Misra, Misra, & Woungang, 2009).

A Mobile Ad Hoc Network was originally developed for the DOD in order to provide an option for quickly deploying communication systems. It is a dynamic peer-to-peer, multi-hop mobile wireless network that is able to function without an

existing infrastructure or prior configuration (Misra et al., 2009). One factor that makes the MANET an appealing option for VBSS missions is that MANET is specifically designed for nodes on-the-move (Aras, 2014). The nodes on-the-move may be individual radios or sensors that transmit or route data. Another advantage of a MANET topology is the fact that it does not require a centralized authority like cellular stations. In addition, MANET is self-forming, self-configuring, and self-healing thereby underpinning a dynamic topology. However, Mobile Ad-Hoc Networks also present some disadvantages in supporting such a flexible network environment. These disadvantages include power consumption; nodes operating in a shared wireless channel; and, quality of service (Misra et al., 2009).

As popularity of, and interest in, MANET/WMNs increased, the IEEE established several working groups to enhance several 802.X protocols to better accommodate MANET/WMNs. Currently, IEEE standards 802.11s, 802.15.1, 802.15.4, 802.15.5, and 802.16a apply more widely to MANET/WMNs. Table 3 summarizes the more common 802.XX protocols (Sichitiu, 2006).

Table 3. 802.XX common protocols

Protocol	Description
802.11s	<ul style="list-style-type: none"> • Amendment for mesh networking, traffic flows in a multi-hop manner from AP to AP improving WMN reliability and scalability • Builds on the limitations of a traditional Access Points (AP) model • APs now have a functionality of a MR
802.15.1	Bluetooth: developed for the Wireless Personal Area Network (WPAN)
802.15.4	<ul style="list-style-type: none"> • ZigBee: also developed for WPAN • Specifically compatible with sensor technology that use low data transmission rates and have long battery life • Addresses power consumption of MANET/WMNs
802.16a	WiMAX: designed to enhance the original 802.16 standard to accommodate MANET/WMN's peer-to-peer multi-hop transmission with lower data rates and better support for quality of service

b. Sample Experiments Utilizing the CENETIX TNT Testbed

Sinsel (2015) tested wireless reachback capabilities for biometric data sharing from the SEEK II biometric collection device to the CENETIX server over a MANET formed by WaveRelay radios. In order for a successful data transfer to take place, the following were necessary:

- One SEEK II biometric collection device with an MPU4 radio connected to the biometric device (connected wirelessly to one quad radio)
- Five WaveRelay quad radios: (1) ship's superstructure, two decks above the main deck; (2) laptop with a wired Ethernet connection; (3, 4) two relay vessels; (5) C2 cell on the Yerba Buena Island, Alameda, California
- VPN access to the CENETIX server located at NPS in Monterey, California

The experiment produced favorable results demonstrating a successful data transfer from the biometric collection device to the CENETIX lab. However, during this experiment, Sinsel (2015) encountered three constraints: (1) radios and antennas specifications, (2) range between nodes, and (3) environmental conditions.

Osmundson and Bordetsky (2014) implemented a mobile ad-hoc networking architecture in a June 2012 experiment held in the Baltic Sea and in Souda Bay, Greece. This experiment "integrated tactical-level boarding teams equipped with hand-held portable and unmanned system-based detectors with geographically-distributed technical experts and data fusion centers." (Osmundson and Bordetsky, 2014, p. 6).

Several other MIO/VBSS experiments were conducted in the boundaries of the NPS CENETIX testbed utilizing either WaveRelay, TrellisWare, virtual extension nodes, or a combination of two or all of the technologies. All of the experiments provided a solid theoretical model, but all demonstrated shortcomings to be improved upon. Table 4 outlines the conclusions and some challenges noted during previous experiments.

Table 4. CENETIX TNT experiments: conclusions

Year, Author	Conclusions
2014; Aras, E.	<ul style="list-style-type: none"> • Two mobile ad-hoc networks (one with WaveRelay and one with TrellisWare radios) and one wireless mesh network (utilizing virtual extension nodes) was tested. • A combination of all three offers the best solution for a boarding team. • With high-frequency WaveRelay solution, at least 17 radios were required to cover a 694-foot-long vessel. • With TrellisWare, only four radios was required; however, only voice data could be transmitted. • Virtual extension nodes are useful for transmitting small amounts of data among board team members. Communication was established with only five nodes.
2014; Stewart, V.E.	<ul style="list-style-type: none"> • Communication gaps when monitoring the network status. • The need for interchangeable, vendor independent hardware and applications (e.g., biometric applications). Without such solutions, TNT would not be able to provide a fully operational solution to meet VBSS requirements.
2012; Koletsios, S.	<ul style="list-style-type: none"> • Line of sight issues: when boats with relay nodes were out of range or in a blind spot, the entire network collapsed. A fixed node or an aerial node, such as a UAV, would possibly solve this issue.
2012; Kontogiannis, T.	<ul style="list-style-type: none"> • The use of relay nodes improved direct communication (up to 14 nautical miles) • Higher antenna placement improved throughput and data rate. • Equipment used is a significant factor (type of equipment and its availability); with proper equipment, communication distance can be improved beyond 14 nautical miles. • Connectivity range is dependent on types of data (voice, video), especially in a network with mobile nodes. • Data can definitely be made available real-time; however, packet loss and network connectivity interruptions were prevalent, which signify that possible loss of vital data is very likely.

c. Other Considerations

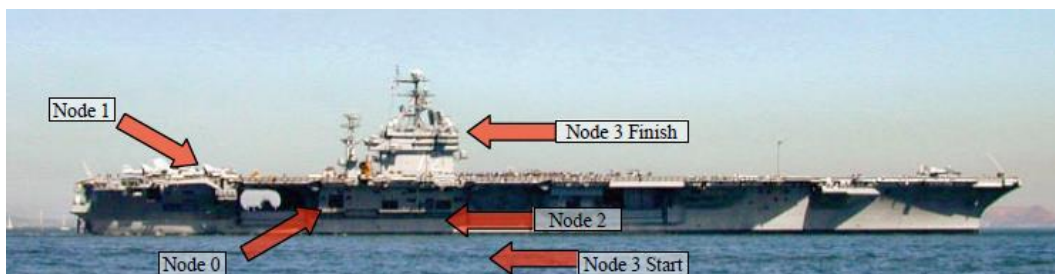
Line of Sight Networks: Edelkind (2012) stated that LOS networks are the most convenient for man-packable and handheld radios. “Rigid Hull Inflatable Boats (RHIBs) are capable of secure voice communication over LOS networks using high-frequency and tactical satellite communications” (Edelkind, 2012, p.

36). Edelkind argued that 4G cellular services are not reliable due to a vessel structure's impact on signal. 4G cellular service only provides a point-to-point communication and not the situational awareness. Additionally, there is no encryption for secure communication.

TrellisWare Radios: In 2007, Blair and colleagues identified communication gaps due to vessel structures. They attempted to resolve this issue by utilizing TrellisWare radios. Edelkind (2012) and Aras (2014) experienced similar communication gaps between the boarding team and a network operation center during their CENETIX TNT testbed experiments.

Blair and colleagues (2007) proposed a testbed design for a tactical mobile mesh network with a high concentration on PHY and MAC levels. They argued that harsh radio frequency environments, such as aboard a vessel, require solutions with robust PHY and MAC layers. Specifically, “the testbed is capable of relaying over up to nine nodes and delivers multiple channels of low-latency, cellular quality, push-to-talk voice over multiple hops” (Blair et al., 2007, p. 1). This concept was tested aboard USS *Midway*, a decommissioned aircraft carrier in the San Diego harbor. Figure 26 depicts the placement of the nodes during the USS *Midway* experiment.

Figure 26. USS *Midway* field test configuration



Source: Blair, A., Brown, T., Chugg, K. M., & Johnson, M. (2007, October). Tactical mobile mesh network system design. In *Military Communications Conference, 2007. MILCOM 2007.* (pp. 1–7).

Blair et al. (2007) described the experiment as follows:

The baseline configuration had four nodes as shown in Fig. [26]. One node was the video sink and was positioned on the hanger deck (Node 0 in Fig. [26]). A second node was on the flight deck with no line of sight to the video sink (Node 1 in Fig. [26]). A third node was two floors below the hanger deck between the hanger deck and the engine room (Node 2 in Fig. [26]). Again there was no line of sight between this relay and the video sink. A roaming node (Node 3 in Fig. [26]) was used to source video from the engine room (approximately 5 floors below the hanger deck). This roaming node proceeded to walk up from the engine room, through the hanger deck, up a closed elevator to the flight deck, and then up into the bridge (approximately 4 floors above the flight deck). This path was walked without packet error (between video source and sink) and with no perceivable impact to video or voice latency. The switching between the relaying nodes occurred without any impact on the end user (< 10 ms voice latency variation and no packet loss). Throughout all testing, low-latency voice communications were on-going between all nodes involved. (6)

Although Blair and colleagues (2007) had a successful test, the USS *Midway* is not a fully operational vessel; it is a museum. Having had a true maritime experiment with a fully operational vessel away from an urban area and existing communication conflicts the test could have had different outcomes.

WIISARD: Chipara and colleagues (2012) presented the Wireless Internet Information System for Medical Response in Disasters (WIISARD) emergency response system that provides reliable communication in a dynamic and or minimal network infrastructure. The WIISARD employs a peer-to-peer architecture. In addition, WIISARD utilizes a gossip-based protocol, data mulling and local communication to disseminate data (Chipara et al., 2012). Chipara and colleagues (2012) presented three key challenges that arise during emergency response situations: “(1) minimize the reliance on network infrastructure during emergency responses, (2) cope with a dynamic radio environment subject to interference, and (3) support communication among mobile users” (p. 407). To demonstrate the WIISARD solution Chipara and colleagues ran an emergency response drill with 19 first responders and 41 victims.

The drill results showed only 10% reliability of the traditional mesh network due to high mobility and network partitions. Furthermore, Chipara et al. (2012) observed high variability in link quality that was attributed to environmental factors such as “wall attenuation, interference, and changes in antenna orientation due to body movement” (p. 415). When Chipara et al. (2012) employed gossip-based protocol with data mulling, they saw a 98% system reliability. Data mulling relies on caching data (in this case patient health data) while gossip-based protocol relies on a local communication versus an end-to-end multi-hop routes (Chipara et al., 2012). Moreover, a gossip-based protocol employs a push, pull, or a combination of the two systems. In general, when gossiping occurs between different nodes, control messages are being pushed and data is being pulled between the nodes. Both, push and pull systems have advantages and disadvantages. Push systems offer better latency and higher fault tolerance; however, this creates redundancy and puts a higher overhead on the system. Pull systems present a lower overhead, but instead suffer from high latencies. Hence, a combination of two systems is usually employed.

6. Interoperability

The ultimate sensors solution should be interoperable with the DOD and VHA EHR systems and possibly other medical facilities. Stevenson, Naiman, Valenta and Boyd (2012) presented a Cursor-on-Target (CoT) as a possible solution for an integrated disease surveillance system that consists of interoperable systems from different agencies involved in emergency responses situations. Such situations may be terrorism attacks, epidemics, natural, and or man-made disasters.

CoT is a message router originally developed by the MITRE Corporation to provide a “common language” for tactical systems (Kristan, Hamalainen, Robbins, & Newell, 2009). CoT messages are written in the Extensible Markup Language (XML), which provides a common format for messaging. CoT consists of a base schema with basic parameters, but it is flexible enough for users of this

messaging schema to be able to define their own message schemas based on specific system needs. The CoT message router is a stand-alone application that can be installed on any computer and its base schema is registered in the DISA DOD XML registry and is available for DOD distribution (Kristan et al., 2009). Some public health organizations utilize Health Information Portability and Accountability Act electronic data interchange X12, and Health Level 7 interfaces, which can be mapped to XML (Stevenson et al., 2012). Data sharing leading to complete interoperability is achievable with CoT's flexibility and health systems' ability to interpret XML.

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III. BENCH AND FIELD EXPERIMENTS

A. INITIALLY PLANNED BENCH AND FIELD EXPERIMENTS

The researchers outlined four sets of experiments, referred to as phases. Each phase builds on lessons learned from the preceding set of experiments. The ultimate planned outcome is to test the selected biomedical sensors in an actual VBSS exercise, with the specific objective to demonstrate near-real time data reachback to an NPS simulated medical server in the CENETIX lab.

The researchers will be outfitted with down-selected wearable biomedical sensors during the third and fourth phases of these planned experiments. These sensors will monitor ambient and physiological conditions. Desired sensor data include blood pressure, respiration and heart rate, ambient temperature, cranial impact force, air quality, and peripheral capillary oxygen saturation. Additionally, relative ground angulation and movement will be measured as a proxy for an assessment determination of the Glasgow Coma Scale.

1. Phase 1: Bench Testing and Baselineing

The researches will test multiple wearables with heterogeneous data streams for collation and bandwidth collaboration. Specific objectives included out of the box configuration, testing, and familiarization.

2. Phase 2: Pre-Field Experiment: Single Sensor Testing

The researchers will test individual wearable biosensors in various environments to test for technology specification throughput and constraints. Environments include maritime, field, rural, and high-density urban areas. Specific quantitative measurements include data throughput, communication distance, and frequency spectrum competition.

3. Phase 3: Pre-Field Experiment: Multiple Sensors Testing

Researchers will wear multiple biosensors in various environments to test for data throughput and signal contention while communicating in the same spectrum. Additionally, qualitative and quantitative evaluation through observation will include ease of use, subjective comfort, and data throughput.

4. Phase 4: Field Experiment in a Maritime Environment

In an applied tactical exercise, the researchers will wear the down-selected sensors and telecommunications equipment. During this phase, the researchers will test for data throughput and reachback to a simulated medical data server.

B. EVALUATION CRITERIA

The researchers developed the following evaluation criteria that were based on data, tactical, human factors, and medical treatment needs derived from the literature review. Each criterion is elaborated below and each down-selected sensor will be accordingly tested for these unless stated otherwise. Table 5 summarizes each criteria and depicts how each criterion fits into the OBHIT evaluation framework.

Form Factor: This criterion directly ties to unobtrusiveness and includes traits such as weight and size. Sensor thickness will be the main size consideration as it is the primary size dimension that contributes to protrusion from the body's surface.

Battery: This criterion not only addresses the battery life affected by power consumption, but also takes into account recharge time for an individual sensor. In scenarios where tactical operators have short rest periods between multi-day missions, it is critical for the sensors to come to a usable charge sufficient to endure the next mission. Due to the scope of this research, recharge times will not be tested as it is assumed that VBSS teams work in eight-hour

shifts with the ability to return to the base ship where time to charge is not a factor.

Transmission Distance: A two-meter transmission distance appears to be sufficient as it has been determined that each sensor should be primarily connected to an on-person mobile computing device as part of a body area network. However, due to recent theoretical work conceived by the researchers on priority signal transmission and master-slave relationship reorientation in a Bluetooth architecture, it has been determined that transmission distance shall be looked at as a criterion (Anderson, McLauchlin, & Montgomery, 2015).

Connectivity: The researchers will evaluate each sensor for network connection at the physical layer as well as for the protocol standard is being used. Additionally, researchers will evaluate whether the current out-of-the-box configuration allows for modularity as previously discussed.

User Friendliness: In line with factors from unobtrusiveness, it is vital for a non-technically inclined individual to easily don the sensor as well as doff it for maintenance and charging. Included in this criteria is user comfort and range of motion.

Data Richness: In order for the wearing of the biomedical sensors to be of any usefulness, it is important that the sensors capture key physiological data and that the captured data is shared via the network. In addition to the pertinent data, sensors should broadcast other data that may prove useful for health monitoring, location triangulation, or sensor network management.

Data Storage: One final consideration is whether the sensors have onboard storage for manual data uploads after missions are completed. Given the constrained signal environment in which VBSS operations take place, it is expected that data packets will be dropped due to interference or lost connection.

Table 5. Sensor evaluation criteria

Dimension	Factor	Criterion	Grading		
			Under 85% from benchmark	Benchmark \pm 15%	Baseline or better
Technical Performance	Effectiveness	Transmission Distance in meters	less than 90	90 - 110	more than 110
		Connectivity	Wired	Closed Wireless (requires vendor receiver solution)	Open Wireless (with API for data sharing)
	Readiness	Ease of deploying sensors in a maritime environment	Major hardware / application configuration required before deployment	Minor configurations required before deployment	Able to deploy out of the box; plug and play
	Implementability	Form Factor Weight in grams <ul style="list-style-type: none"> • Sensor only • Sensor & Straps Thickness in mm	more than 13 more than 70	11 - 13 50 - 70	less than 11 less than 50
		User Friendliness (subjective measurements on sliding scale)	Not intuitive design Difficult to don/doff Charging difficult		Very intuitive design Easy to don/doff Wireless charging
	Reliability	Battery (in hours of operating time between charging)	less than 8	8 - 10	more than 10
		Data Storage	Does not locally store physiological measurements that were transmitted	Has sufficient local storage for physiological measurements to keep track of an 8-hour mission set	Can store multiple days of physiological measurement data
Information Quality	Data Relevance	Data Richness Variety of data	Provides data on single physiological or ambient measurements	Additionally provides data on multiple physiological or ambient measurements	Additionally provides data useful for location triangulation or network management
System Quality	Data Accuracy	Data Utility (data accuracy in health status measurements only) Data Accuracy (all measurement sets from the originator)	Measurements are under 85% from benchmark	Meets benchmark measurements \pm 15%	Meets or exceeds baseline measurements

C. EQUIPMENT USED IN THIS RESEARCH

Based on the sensor selection criteria outlined in Chapter III, Section B, the researchers elected to perform tests with the already acquired Zephyr BioHarness 3 (BH3) from Medtronic. Additionally, in order to test multiple sensors in a WBAN, the researchers also tested NPS acquired Triax SIM-G and SIM-P sensors. This approach of incrementally adding commercial off the shelf sensors into the presented conceptual model serves as a proof of concept for the use of multiple biomedical sensors in a tactical environment.

1. Sensor System Description

The sensors used in this research were acquired by the Naval Postgraduate School in two increments. The BH3 sensors are part of ongoing research, which began in 2014 with the efforts of Coates and Urquidez while working with the CENETIX lab. The Triax sensors were acquired in 2015 to provide additional physiological measurements that could not be captured by the BH3. When used together, the two sensors provide an opportunity for the researchers to validate their conceptual model of using multiple biomedical sensors to capture meaningful health status information on operators in a tactical environment.

a. *Zephyr BioHarness 3*

The BioHarness 3 (Figure 27) is a physiological monitoring device (the sensor) that is inserted into a chest strap, compression shirt, or loose fit shirt (Figure 28). It is designed to communicate via Bluetooth or IEEE 802.15.4 to a laptop that is running the OmniSense software suite. A separate software development kit for Android is available to allow the BH3 to communicate with smartphone applications (Zephyr Technology, 2012).

This sensor was tested in an out-of-the-box configuration with the sensor inserted into the provided chest harness. The combined sensor and support

harness weighs 120 grams and projects a 21 mm obstruction from the wearer's body surface.

Figure 27. Zephyr BioHarness 3 sensor



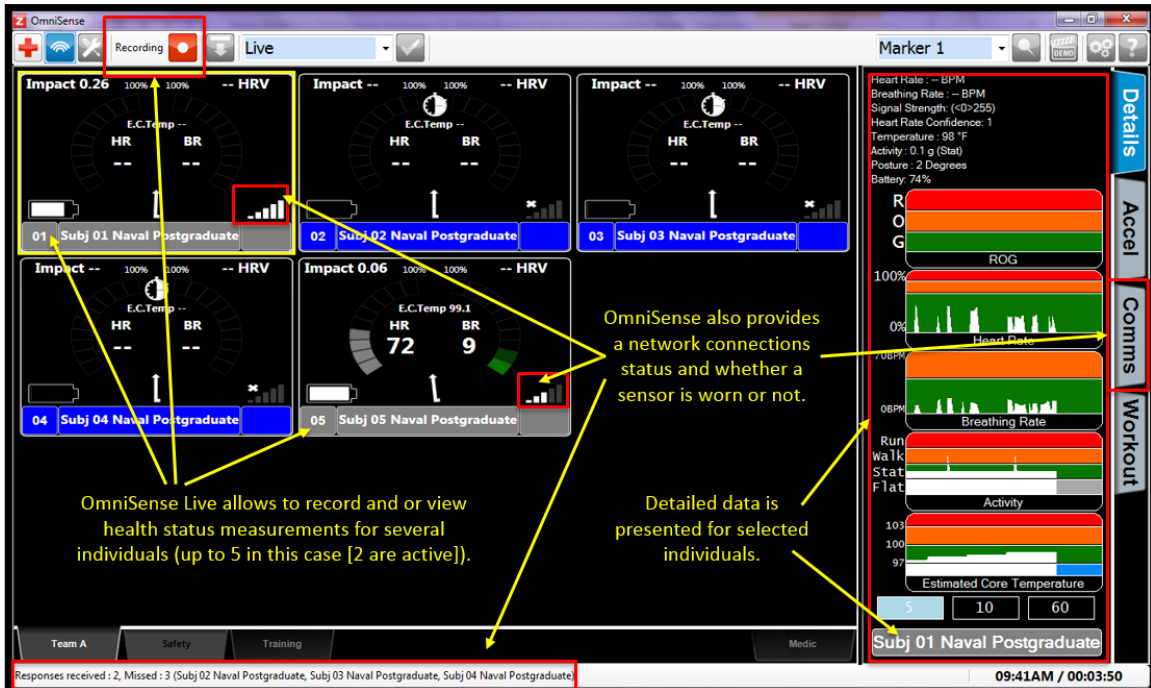
Figure 28. BH3 inserted into chest strap and affixed on a mannequin



Source: Biopac Systems, n.d. Bioharness Telemetry & Logging Systems. Retrieved February 1, 2016, from http://www.biopac.com/product/bioharness-telemetry-logging-systems/?attribute_pa_size=data-logger-and-telemetry-physiology-monitoring-system

The BioHarness 3 sensors transmit data to the OmniSense Live application (Figure 29).

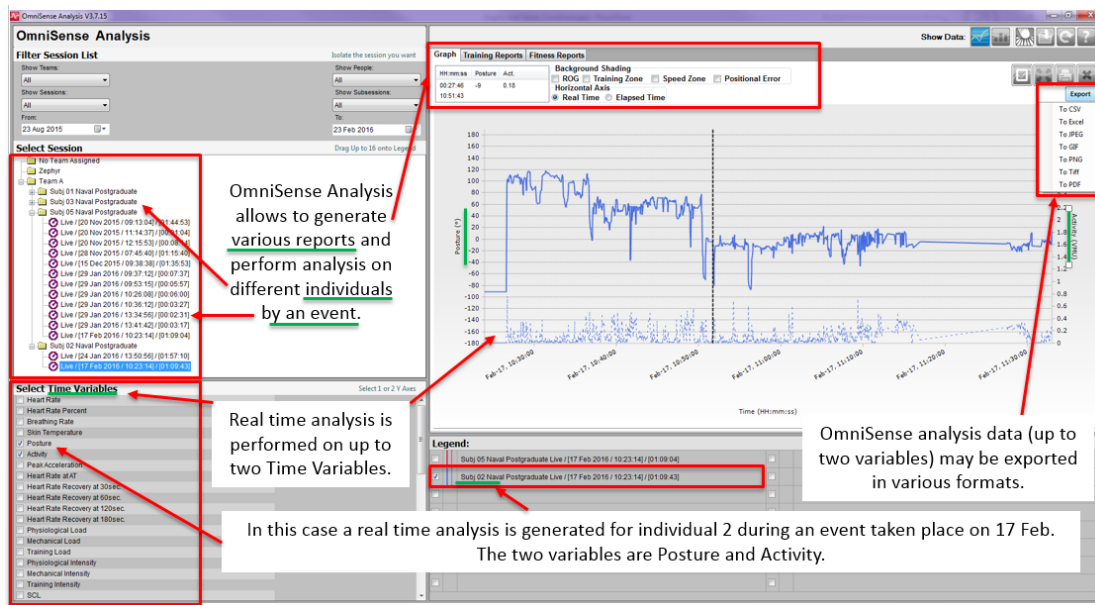
Figure 29. OmniSense Live recording health status measurement for two individuals



The OmniSense software suite (OmniSense) is a client application, which must be installed on a Windows compatible computer. It is presumed that in an applied VBSS tactical setting this computer would be collocated with the boarding officer as part of the command and control (C2) function.

The OmniSense software suite is comprised of two major applications, which provide live visualization of health status information (Figure 29) and facilitates data analysis and data export (Figure 30).

Figure 30. OmniSense Analysis graphically depicting posture and activity



b. Triax SIM-G

The Triax SIM-G sensor (Figure 31) is designed to be inserted into a head strap, knit cap, or even integrated into a helmet (Figure 37). This sensor transmits triaxial data using a three-axis accelerometer to a vendor specific sensor receiver, SKYi (Figure 32), over a 900 MHz band (Triax, 2014). The SKYi receiver must be connected to a wireless 802.11 access point in order to transmit collected sensor data to the Triax Cloud for analysis and viewing. This sensor receiver also has a readout display that provides a chronological history of the most recent 20 impacts received on the device during the current recorded session.

Figure 31. Triax SIM-G sensor

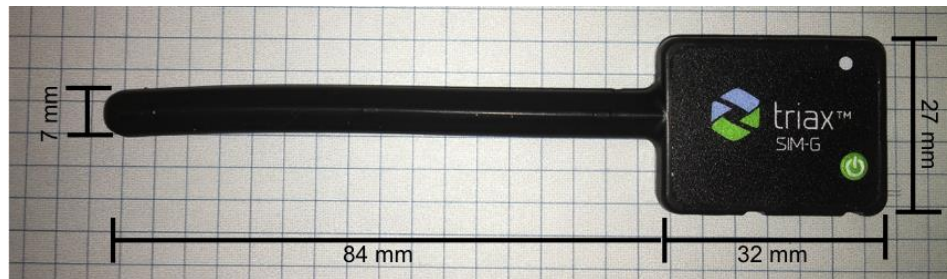


Figure 32. Triax SKYi sensor receiver



(1) SIM-G Data Visualization

All impact data that are recorded in the Triax Cloud provide authorized users with a means to visualize impact data over a timeline (Figure 33). Additionally, each data point can be selected to provide an impact detail view (Figure 34) with a three-dimensional model that a user can rotate (Figure 35).

Figure 33. Impact timeline with Peak Linear Acceleration measured in g-forces

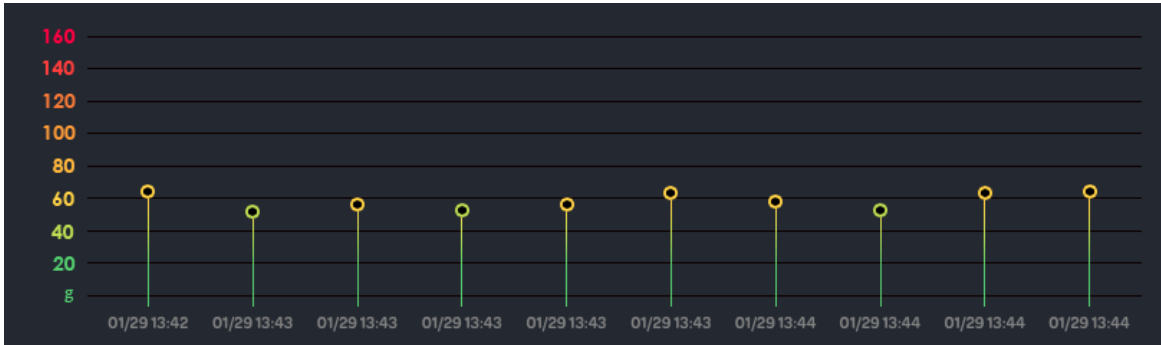


Figure 34. Sample impact detail view of simulated impact administered during testing

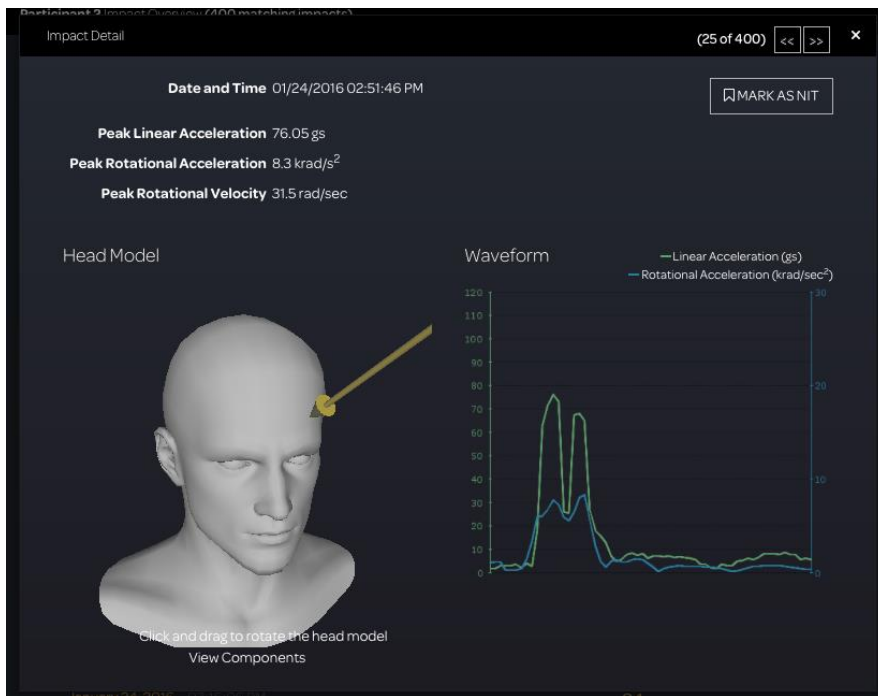
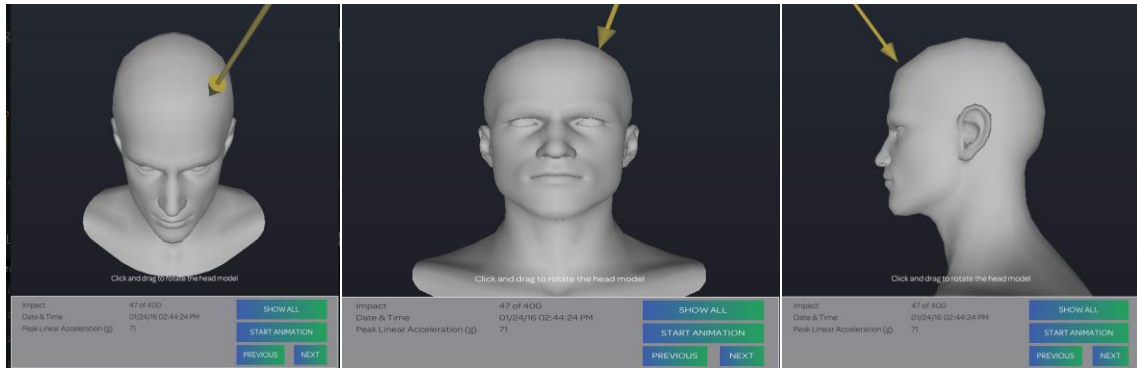


Figure 35. Three sample perspectives using the rational head model



c. Triax SIM-P

The SIM-P sensor (Figure 36) uses the same technology to capture g-force data from impacts as the SIM-G sensor. However, it transmits data via Bluetooth to an associated iOS device that is running the Triax SIM-P app. This sensor is worn in the same manner and types of headbands or skull caps as the SIM-G sensor (Figure 37). Unlike the SIM-G sensor, the SIM-P sensor can maintain a record of up to 200 data points in its onboard memory. This capability facilitates deferred data synchronization when the sensor is not within vicinity of its associated iOS device.

Figure 36. Triax SIM-P sensor

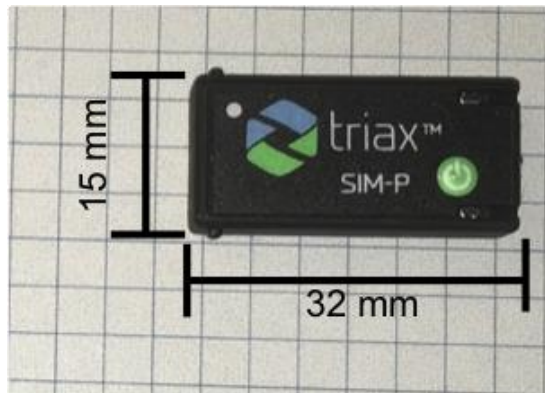


Figure 37. Headband with SIM-P sensor and the Triax SIM-P app



Source: PR Newswire, (2014, October 29). Abby Wambach joins Triax team to encourage head impact monitoring for better safety and improved training technique. Retrieved February 1, 2016 from <http://www.prnewswire.com/news-releases/abby-wambach-joins-triax-team-to-encourage-head-impact-monitoring-for-better-safety-and-improved-training-technique-280769802.html>

(1) SIM-P Impact Data Register

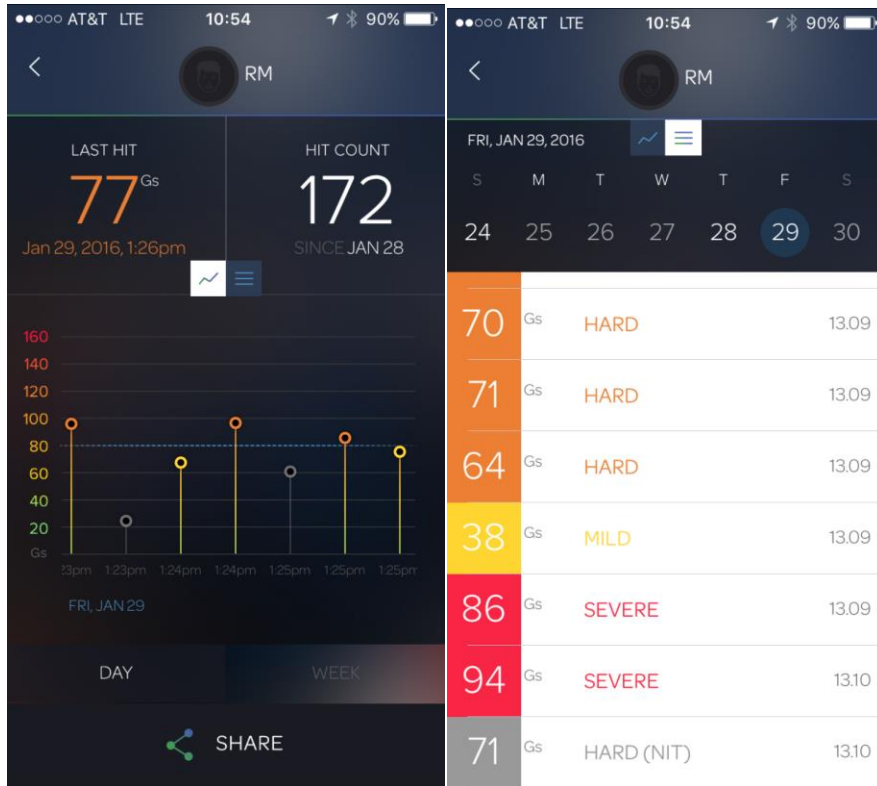
As previously discussed, the SIM-P is outfitted with an onboard memory to store the most recent 200 registered impacts. Opportunistic synchronization takes place when the sensor is within the Bluetooth transmission range of its associated iOS device and the Triax SIM-P app is running. For this reason, it was not possible to conduct a differential analysis of data residing on the sensor versus data shared with the iOS app. The researchers however conducted similar impact tests as with the SIM-G series sensors.

(2) SIM-P Data Visualization

Similar to the Triax Cloud visualization, the SIM-P app provides users with an interface that lists each sustained impact (Figure 38). The app however lacks an interface to visualize impact location on a head model as the Triax Cloud solution does. Additionally, while it is possible to manually share saved data via

email, no option exists to have data automatically synchronize with a cloud platform.

Figure 38. Triax SIM-P interface on an iOS device



2. Measurement Capabilities

Table 6 provides an overview of sensor measurement capabilities. These capabilities are matrixed to the key tactical and population health measurements presented in the previous chapter, which are deemed vital to assessing operator health status and population health within the organizational layers of DOD and Defense Health.

Table 6. Sensor specifications and capabilities matrix

	Sensor		
	Zephyr BH3	Triax SIM-G	Triax SIM-P
Specifications			
Dimensions	47mm diameter	Body: 34mm x 27mm Antenna: 84m x 7mm	32mm x 15mm
Thickness	11mm	7mm	8mm
Weight	18g	11g	6g
Radio	Bluetooth 4.0 IEEE 802.15.4	900 MHz proprietary	Bluetooth 4.0
Heart Rate	•		
Breathing Rate	•		
Core Temperature			
Glasgow Coma Scale	• ¹	• ²	• ²
Blood Pressure			
Concussion		•	•
Air Quality			

Note 1: Glasgow Coma Scale proxy measurement through activity.

Note 2: While the sensor does not register regular movement, it can be configured to register activity similar to the BH3 and serve as a proxy for Glasgow Coma Scale.

D. EXPERIMENTS CONDUCTED

Due to the initial availability of only one type of biomedical sensor, the researchers commenced bench experimentation with the Zephyr BH3. This specific sensor meets the selection criteria for physiological and environmental measurements. This sensor was tested in accordance with the criteria from the preceding section with the results as well as the testing criteria presented in Table 6.

1. Phase 1: Bench Testing and Baseline

During this experimentation phase, the researchers familiarized themselves with the sensor documentation, software, and functionality. They also conducted basic connectivity and data capture tests in testing environments with minimal 2.4 GHz interference. The researchers conducted a separate virtual meeting with the regional Triax representative in order to review the SIM-G sensor receiver setup process.

As originally planned, the researchers performed individual sensor tests to obtain baseline data throughput in near-optimal conditions. The primary objectives of these tests were to assess the following:

- Ratio of data points received versus recorded on the sensors (on the BH3)
- Number of impacts recorded versus administered (on the Triax sensors), and
- Possible signal interference from multiple sensors operating in the same locality over the same radio spectrum (both BH3 and Triax sensors)

Additionally, the researchers assessed the maximal link distance as well as time synchronization. Due to the acquisition of data from multiple sources, disparate information was normalized into a useful data scheme for analysis.

The researchers wore BH3 sensors to obtain data for baseline testing and benchmarking. Specific BH3 sensor measurements pertinent for healthcare professional actionability (data utility) include heart rate (HR), breathing rate (BR), posture and activity.

In order to obtain head impact data for the Triax sensors, the researchers followed the vendor representative recommendations. Specifically, sensors were cupped in a hand and then struck against a surface.

Finally, the researchers also tested third-party Android applications in order to assess alternative reachback. Several applications have been marketed as BH3 compatible, capable of acquiring sensor data and then transmitting these

to a Cloud application. For this part of the bench test, the researchers used two tablets, a Pantech P4100 and a Google Nexus 7.

2. Phase 2: Pre-Field Experiments: Single Sensor Testing

For this experimentation phase, the researchers opted to scope down the testing environments. The researchers rationalized that testing in a field and high density urban area was excessive for the focus of this work. Bench testing for Phase 2 was therefore limited to a large open area in a rural city as well as a quasi-maritime environment using the municipal wharf.

a. Phase 2.a: BioHarness 3

For the first portion of this experiment, the researchers selected a large parking lot near the Monterey wharf (Figures 39 and 40) with roughly 270° LOS from a central collection point. The researchers also took note of the number of 802.11 wireless access points that were covering the area, as the BH3 sensor uses wireless protocols that ride on the same 2.4GHz spectrum.

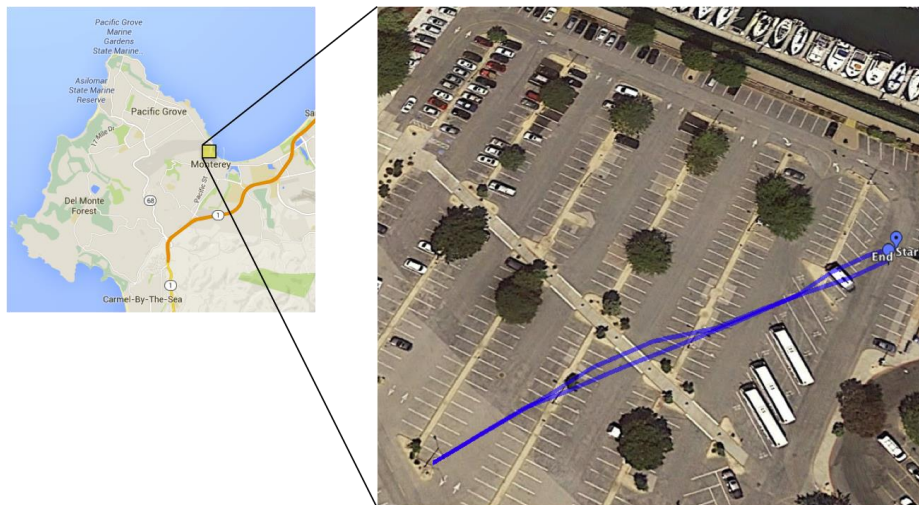
During this experiment, Researcher 1 wore the BH3 sensor and tracked GPS coordinates using an Apple iPhone 6s. Researcher 2 monitored sensor connectivity to the ECHO gateway on the acquiring node at the central collection point. The Lenovo laptop with the OmniSense software acted as the central collection point. The two researchers maintained continuous voice contact via the cellular network so that distance boundaries could be marked as waypoints in the MotionX-GPS app installed on the researcher's iPhone.

The objective for this experiment was to test for throughput and maximum connectivity distance over 802.15.4 (in this text interchangeable used with ECHO) as well as over Bluetooth. Additionally, the researchers used this experiment to make subjective judgements to the non-obtrusiveness factors previously discussed. Finally, this experiment provided the researchers with the first set of data for follow-on analysis.

Figure 39. Mapped track depicting maximal distance boundaries

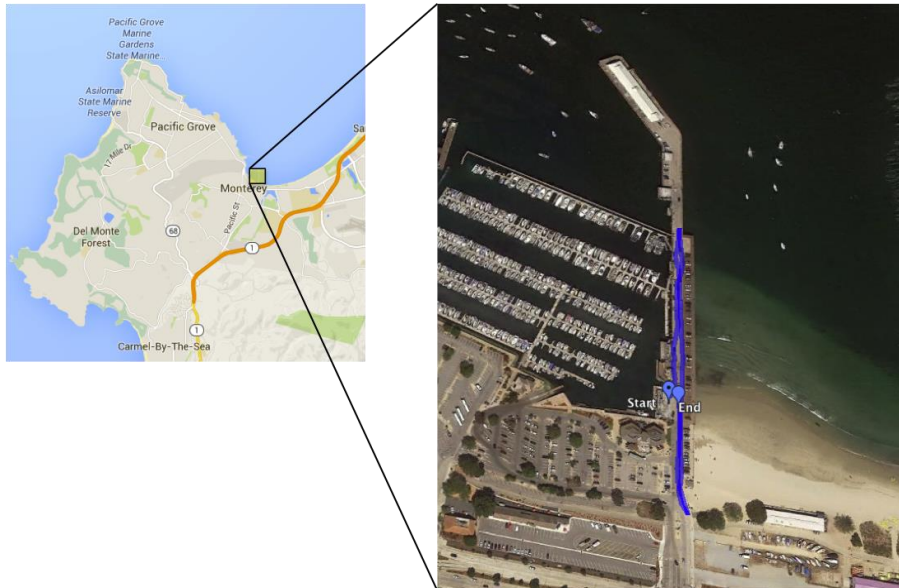


Figure 40. Mapped straight line track for maximal distance test



For the next portion of this phase, the researchers moved to the Monterey Municipal Wharf 2. The Researcher 2 monitored connectivity from the base of the pier (Figure 41) and remained in contact with Researcher 1 via cellphone.

Figure 41. Mapped straight line track for maximal distance test over water



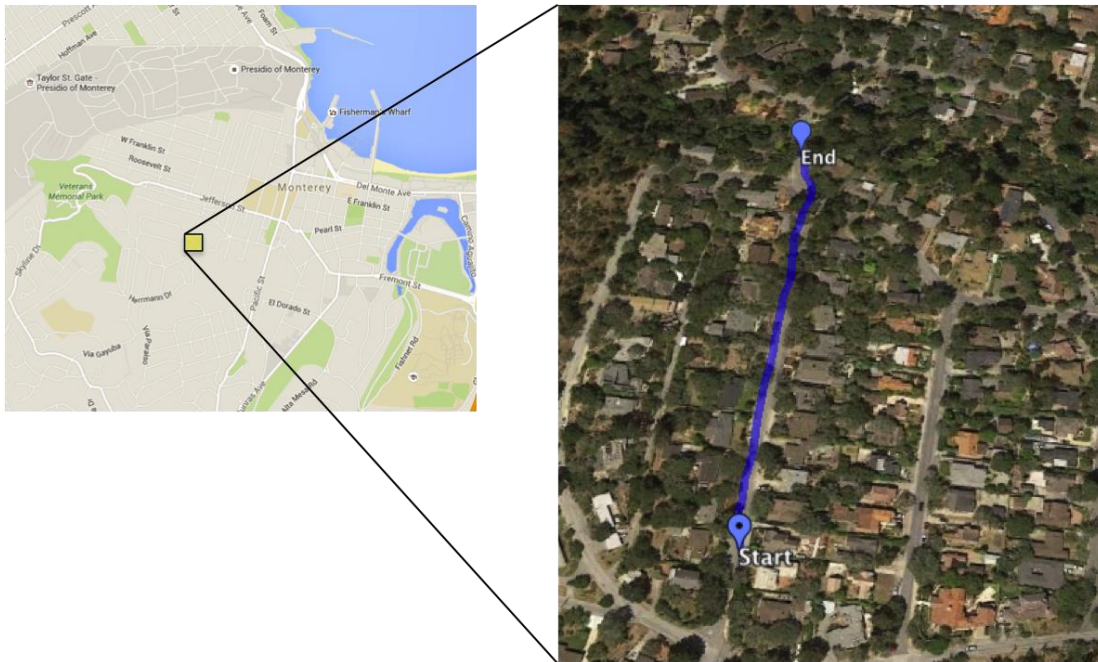
b. Phase 2.b: SIM-G

The researchers acquired four concussion sensors (two SIM-P and two SIM-G) from Triax for experimentation. Similar testing protocols were used as for Phase 2.a. In order to diversify the environment, the researchers selected an alternate testing location with optimal LOS that also represented a rural setting (Figure 42).

As with the Phase 2 experimentation protocol, Researcher 2 monitored the Triax SKYi sensor receiver at the central collection point. Researcher 1 moved with the sensor along the pre-designated route. Both researchers maintained contact using their cellphones and RM's location was tracked as before.

The researchers conducted two sub-experiments with the SKYi receiver and SIM-G sensor. Both tests were designed to test maximal distance from the central collection point, with the receiver's antenna facing towards the sensor in one experiment and then away from the sensor in the follow-on experiment.

Figure 42. Triax SKYi Test: Monterey suburban area



3. Phase 3: Pre-Field Experiments: Multiple Sensors Testing

In line with the planned experiments for this phase, the researchers conducted testing using the SIM-P, SIM-G, and two BH3 sensors in an environment with minimal spectrum congestion. The objective of this phase was to test for potential signal interference as well as maximal data transfer distance of each of the sensors collocated on an individual.

The researchers selected a local football field (Figure 43) for testing due to the minimal 2.4 GHz spectrum congestion as well as for the layout of the field with 10 yard (9.144 m) markings. During this phase, Researcher 2 was outfitted with two BH3 sensors and carried one SIM-P and one SIM-G sensor. One BH3 sensor was worn in the vendor prescribed harness location while the other was worn in a secondary location to act as a quasi-control for data throughput measurement. The Researcher 2 traversed a pre-set South-North path and conducted impacts on the SIM-P and SIM-G sensors every 10 yards. Additional impacts were conducted at four pre-designated locations off of the field (Figure

44). Several iterations of the same testing procedure were conducted to account for various antenna placements and possible interference of different wireless protocols (Table 7).

Figure 43. Phase 3 experimentation location

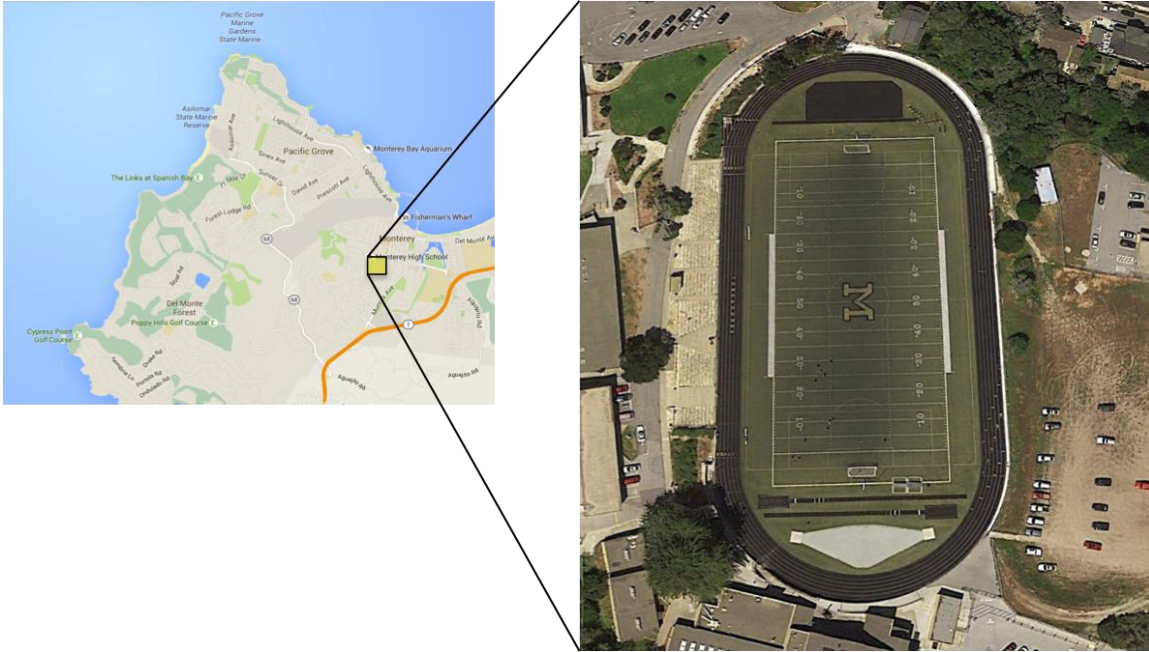


Figure 44. Impact test markers

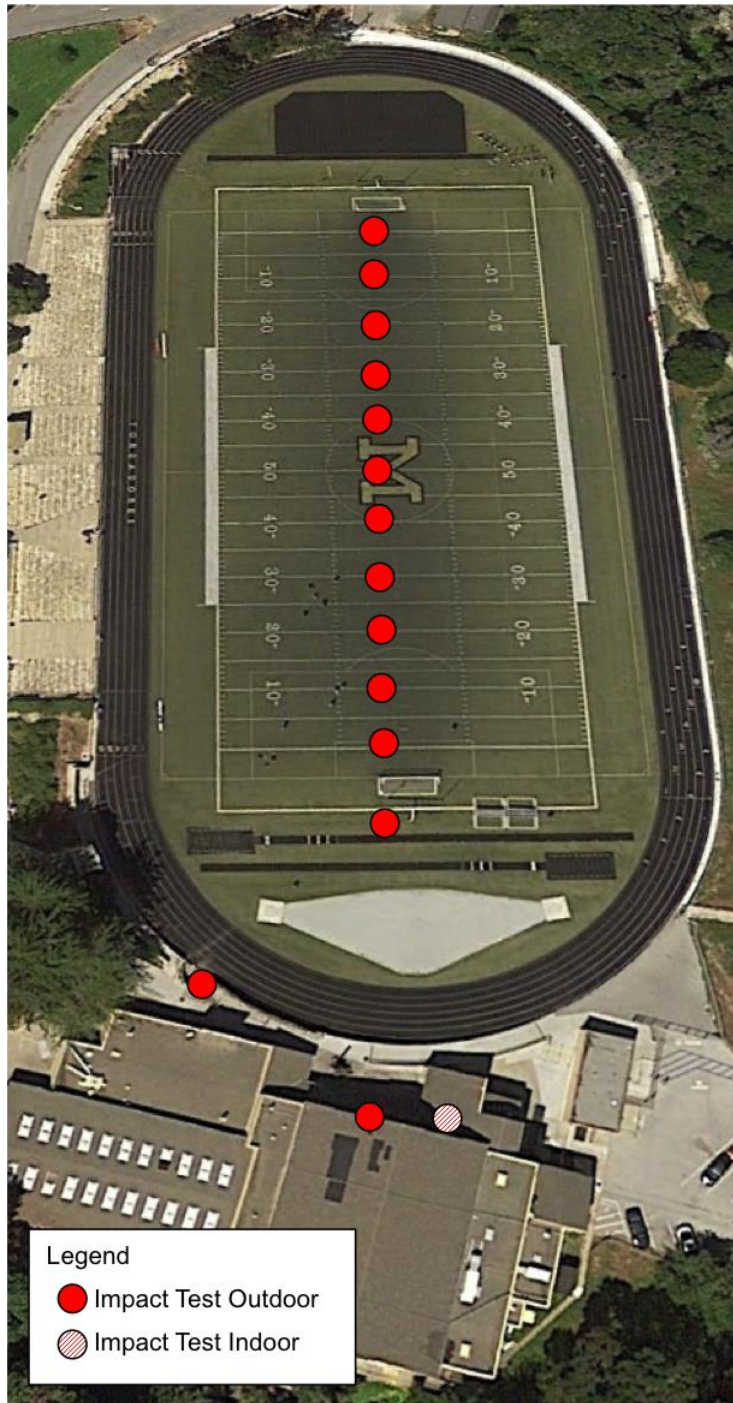


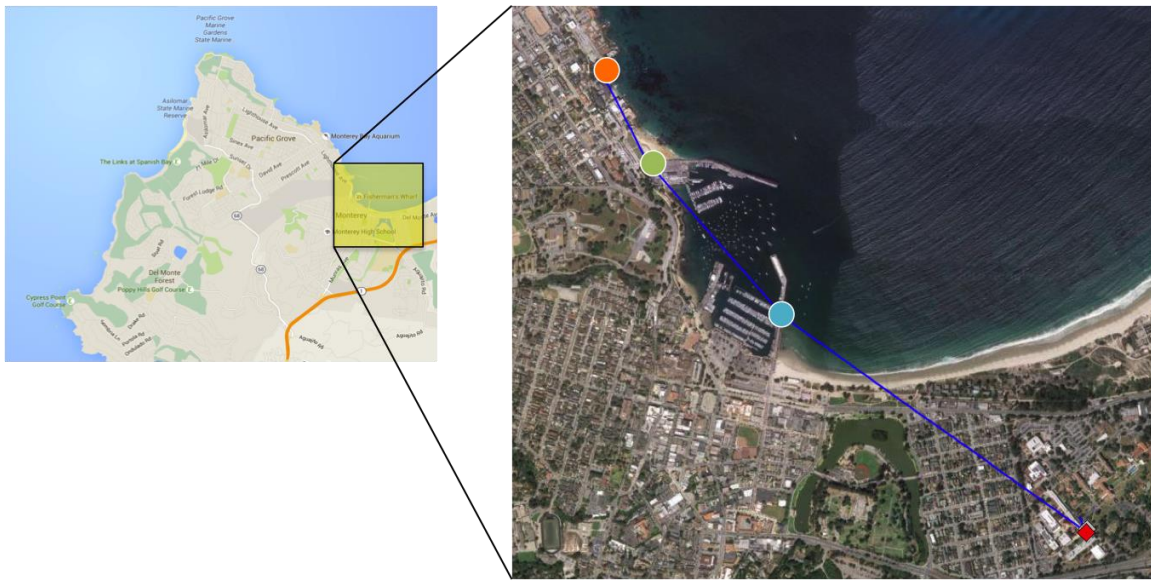
Table 7. Phase 3 experiment outline

Test No.	Sensors Used	Procedure
Round 1	BH3-1 BH3-3 SIM-P 0224 SIM-G 2922	Sensor receivers placed at ground level with antennas facing in direction of Researcher 2. Researcher 2, wearing sensors, follows South-North path and conducts impact tests every 10 yards and at four pre-coordinated off-field locations. BH3 sensors connected via ECHO.
Round 2	BH3-1 BH3-3 SIM-P 0224 SIM-G 2922	Same as Round 1, but receiver antennas are facing away from Researcher 2 (sensors).
Round 3	BH3-1 BH3-3 SIM-P 0224 SIM-G 2922	Same as Round 1, but using Bluetooth versus ECHO.
Round 4	BH3-1 BH3-3 SIM-P 0224 SIM-G 2922	Same as Round 2, but using Bluetooth versus ECHO.
Round 5	BH3-1 BH3-3 SIM-P 0224 SIM-G 2922	Same as Round 1, but the SKYi antenna raised at 2.7 meters.
Round 6	SIM-P 0224 SIM-G 2922	Focus is on SKYi. The receiver is on a ground, facing Researcher 2. Researcher 2, wearing sensors, follows South-North path along the East in-bound line BH3 sensors connected via ECHO.
Round 7	SIM-P 0224 SIM-G 2922	Same as Round 6, but the SKYi receiver is up at 1 meter.
Round 8	SIM-P 0224 SIM-G 2922	Same as Round 6, but the SKYi receiver is facing away from Researcher 2 (the sensors) and Researcher 2 follows South-North path along the West in-bound line.
Round 9	SIM-P 0224 SIM-G 2922	Same as Round 6, but the SKYi receiver is up at 1 meter.

4. Phase 4: Pre-Field Experiment: CENETIX Testbed Testing

In preparation for the Phase 4 experimentation, the researchers conducted throughput testing on the CENETIX TNT testbed. The researchers used an MPU4 WaveRelay radio from Persistent Systems to conduct server pings from three locations (Figure 45). Each location had a clear LOS to the CENETIX antenna, which is located on top of Spanagel Hall at NPS.

Figure 45. Throughput performance of the MPU4 on the CENETIX network



Ping Location	Aerial Distance	Average Throughput	Antenna
● Monterey Wharf	1,600 meters	4.13 Kbps	10 dBi Yagi
● Coast Guard Pier	2,375 meters	11.13 Kbps	10 dBi Yagi
● Monterey Plaza Hotel	2,810 meters	0.43 Kbps	10 dBi Yagi

Upon completion of testing at the Monterey Wharf location, the researchers calculated that the 10 dBi Yagi antenna contributed to a 50% gain in throughput performance. Because of this finding, the researchers down-selected the Yagi antenna for the Phase 4 experimentation.

5. Phase 4: Field Experiment: VBSS Aboard *GTS Adm W.M. Callaghan*

The researchers conducted applied experimentation in a tactical-like setting on board the *GTS Adm. W.M. Callaghan* (Figure 46). The objective of this experiment was to test for the throughput, the maximal reach of the sensor network, and for reachback to the Triax Cloud via a MANET.

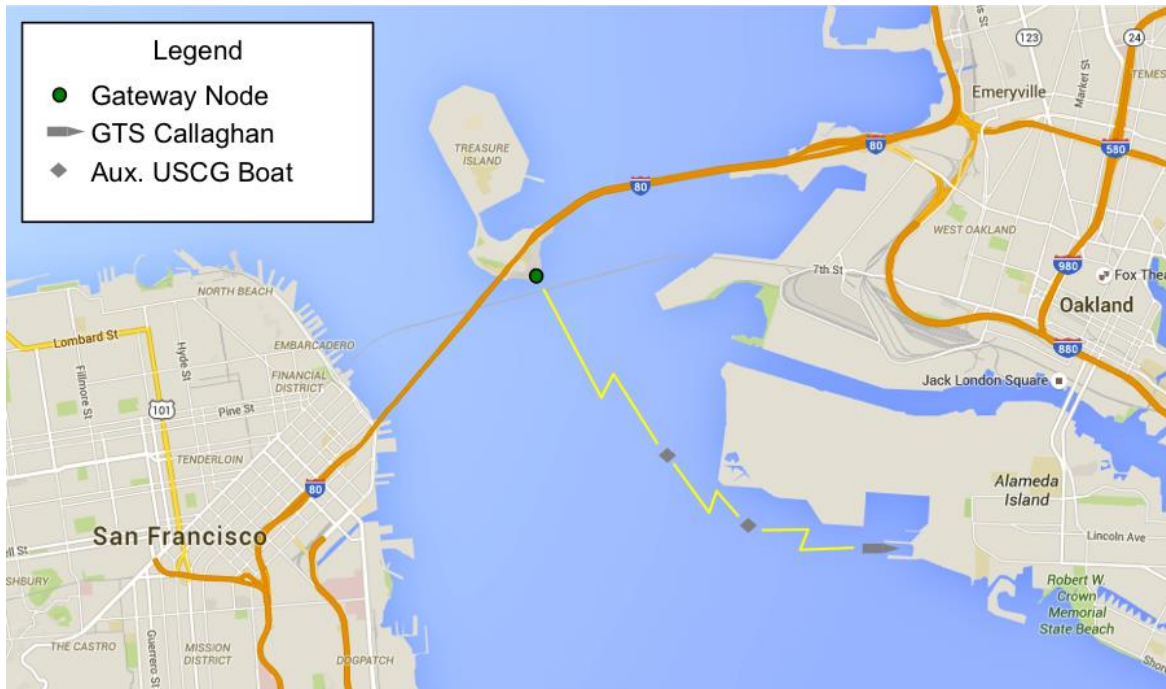
Figure 46. Maritime Administration's *GTS Adm. W.M. Callaghan* berthed in Alameda, California



Source: USNS Admiral W.M. Callaghan (T-AKR-1001), n.d. In *Wikimapia*. Retrieved February 18, 2016, from <http://wikimapia.org/8767956/USNS-Admiral-W-M-Callaghan-T-AKR-1001>

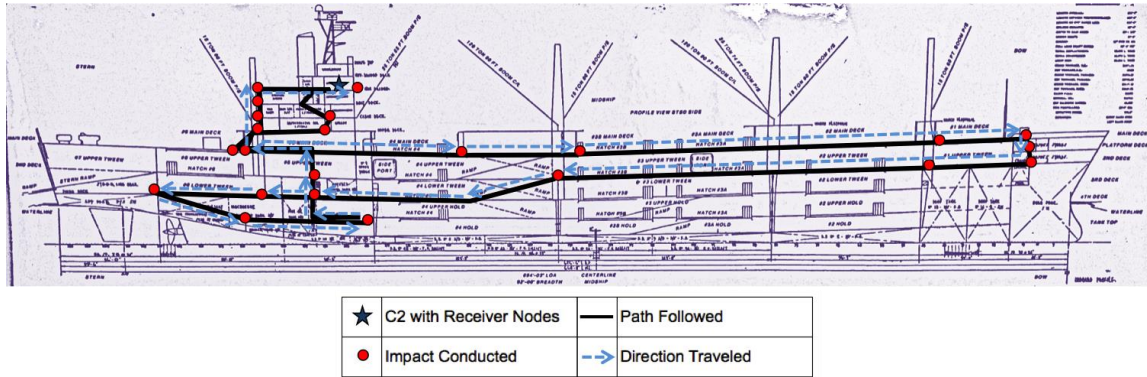
As outlined in standard operating procedures for VBSS operations, the researchers established a C2 presence on the bridge. Command and control for this experiment was comprised of MANET connected sensor receiver nodes that were directionally oriented toward the bow of the ship. The researchers leveraged two Auxiliary Coast Guard boats with MPU4 radios to overcome the communication gaps between the ship and the gateway antenna on Yerba Buena Island (YBI) (Figure 47).

Figure 47. Planned network reachback to gateway via auxiliary U.S. Coast Guard boats



To simulate the infiltration phase of a VBSS operation, the researchers accompanied a two-person Coast Guard boarding team around the ship. Following a standard initial safety inspection (ISI) pattern, the team moved down the superstructure, forward on the main deck, and then progressively searched the lower decks (Figure 48). Researchers were equipped with the Zephyr BH3, Triax SIM-P and Triax SIM-G sensors and conducted impact tests on the Triax sensors at various locations on the ship.

Figure 48. Initial safety inspection sweep path with locations of simulated head impacts



The auxiliary boats with the relay radios were required to abort experiment during the initial ISI sweep due to inclement weather. This forced the researchers to revise the network configuration mid-experiment and attempt a point-to-point connection by directionally reorienting the Yagi antenna towards YBI (Figure 49).

Figure 49. WaveRelay radio with Yagi antenna



For the second iteration of the experiment, the researchers established a Triax Cloud reachback via a mobile hotspot. All other procedures were carried forward from the prior ISI sweep, to include the acquisition of BH3 data over the ECHO gateway.

6. Research Limitations

During bench tests and field experiment, the researchers encountered several limitations. The first limitation was lack of simulated health data server at NPS to serve this proof of concept solution. This limitation was mitigated by using the Triax Cloud as the health data server. Secondly, the researchers encountered challenges connecting to the Internet via the MANET due to environmental conditions. The researchers mitigated this limitation by including a secondary communication path that leveraged a mobile hotspot. Finally, the researchers were not able to conduct realistic concussive force impacts with a control to limit g-force variability of SIM-G and SIM-P sensors. This limitation could only be partially mitigated by using sensor-in-hand impact tests.

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IV. DATA ANALYSIS AND FINDINGS

A. PHASE 1: BASELINING

The researchers were primarily concerned with five perspectives for the analysis conducted on the sensors and the sensor networks. Specifically, these were data throughput, data utility, data accuracy, maximal link distance, and reachback. The researchers addressed additional confounding variables where appropriate and included these in this chapter. The following are definitions for contextual clarity. For an expanded definition of the following terms refer to Appendix A.

- Data throughput: ratio of number of measurement sets received to the number of measurement sets sent from the sensor. This measurement does not test for accuracy.
- Data utility: ratio of number of measurement sets received that match the original data recorded on the sensor. This metric assesses data accuracy in health status measurements only.
- Data accuracy: similar to data utility, but in addition to health status measurements, includes all measurement sets from the data originator.
- Maximal link distance: an assessment of the maximum distance achievable between the sensor and its receiver node that allows for data transfer.
- Reachback: an assessment of the data throughput that occurs between the acquiring node and a Cloud-based data repository.

1. Data Throughput

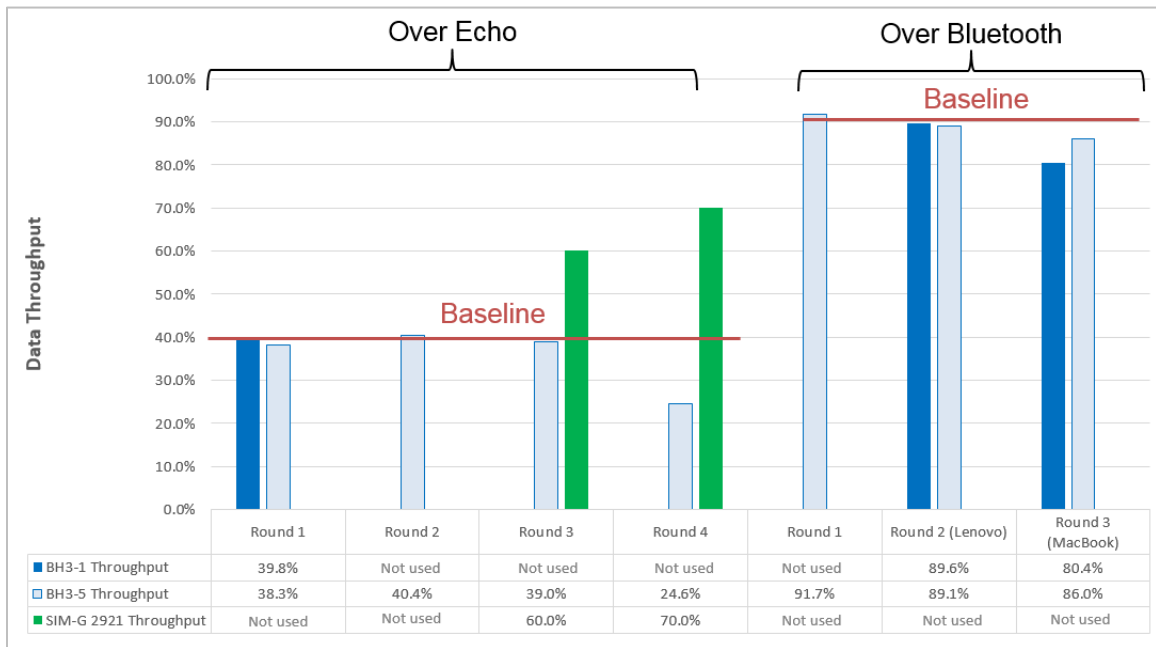
Researchers established data throughput as a metric of network performance in the absence of having software tools that conduct traffic analysis on ECHO and Bluetooth networks. Specifically, they measured data received on the acquiring node to data transmitted from the BH3 sensor during the same testing period.

This measurement schema does not account for data accuracy. Instead, data throughput only accounts for full measurement sets received. The researchers assess data accuracy separately in this chapter.

a. Zephyr BioHarness 3

The researchers noted that data throughput varied based on type of a test performed. Figure 50 depicts throughput varying from 24.6% to 91.7%.

Figure 50. Phase 1: data throughput

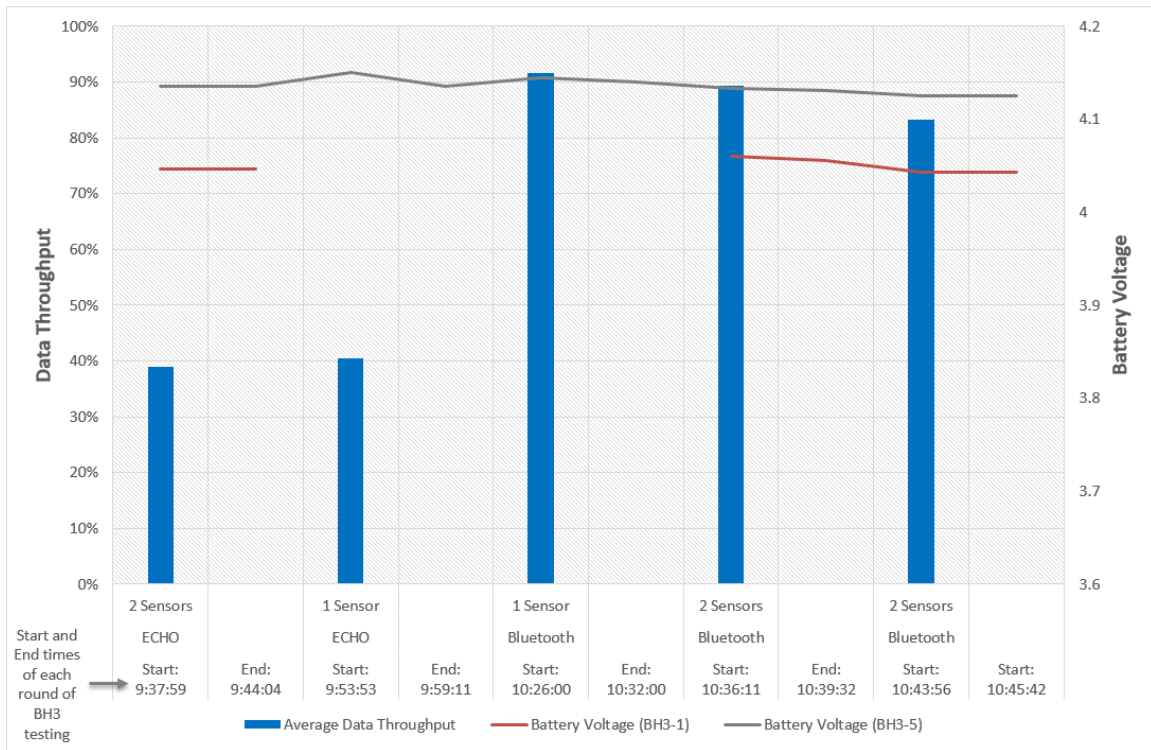


The lowest throughput was recorded for sensor BH3-5 over ECHO gateway during SIM-G 2921 testing. The highest throughput of 91.7% was recorded for sensor BH3-5 during a single BH3 sensor test over Bluetooth. Based on the results of the tests performed in this phase, the researchers established the following throughput baseline: 39.5% over ECHO gateway and 90.1% over Bluetooth.

(1) Battery Voltage

Per specifications, the battery voltage of a Zephyr BH3 sensor varies from 3.6 volts when fully discharged to 4.2 volts when fully charged. During the first five rounds the battery of BH3 sensor 1 (BH3-1) depleted by 0.42% in 9.5 minutes while the battery of BH3 sensor 5 (BH3-5) depleted by 0.48% in 19.7 minutes (Figure 51).

Figure 51. Phase 1: average data throughput and sensor battery depletion by voltage



Sensor BH3-5 was connected continuously while BH3-1 was turned off between rounds. It appears that the battery depletes faster when a sensor is being turned on and off. In general, the battery depletion was not significant and did not affect the throughput.

(2) Intermittent Connectivity

OmniSense application uses proprietary protocols to communicate with sensors and does not offer network management tools to analyze network traffic between sensors and the OmniSense receiver. The only available tool to determine if a connection has been established are the Bluetooth parameters in the OmniSense application suite. Specifically, these are Link Quality, Received Signal Strength Indication (RSSI), and Transmit (TX) Power. However, there are no parameters to analyze network traffic when using the ECHO gateway. Further Phase 1 analysis utilized the Bluetooth parameters in an attempt to explain such a large difference in data throughput. Table 8 outlines the percent of time the Bluetooth connection link between a BH3 sensor and the OmniSense system was down.

Table 8. Phase 1: percent of time Bluetooth link was down

H/W	# of sensors	Sensor	Data throughput	Omni			Sensors		
				% of time RSSI down	% of time Link down	% of time TX down	Link % down	RSSI % down	TX % down
Lenovo	1 Sensor	BH3-5	91.7%	37.1%	0.9%	0.0%	1.8%	36.4%	0.0%
	2 sensors	BH3-1 BH3-5	89.6% 89.1%	Invalid data 15.6%	3.2% Not available	Invalid data 0.0%	Invalid data 1.1%	Invalid data 19.4%	Invalid data 0.0%
MacBook	2 sensors	BH3-1	80.4%	Invalid data	Not available	Invalid data	Invalid data	Invalid data	Invalid data
		BH3-5	86.0%	86.0%	0.0%	0.0%	0.0%	72.1%	0.0%

The following section expands on the values presented in Table 8.

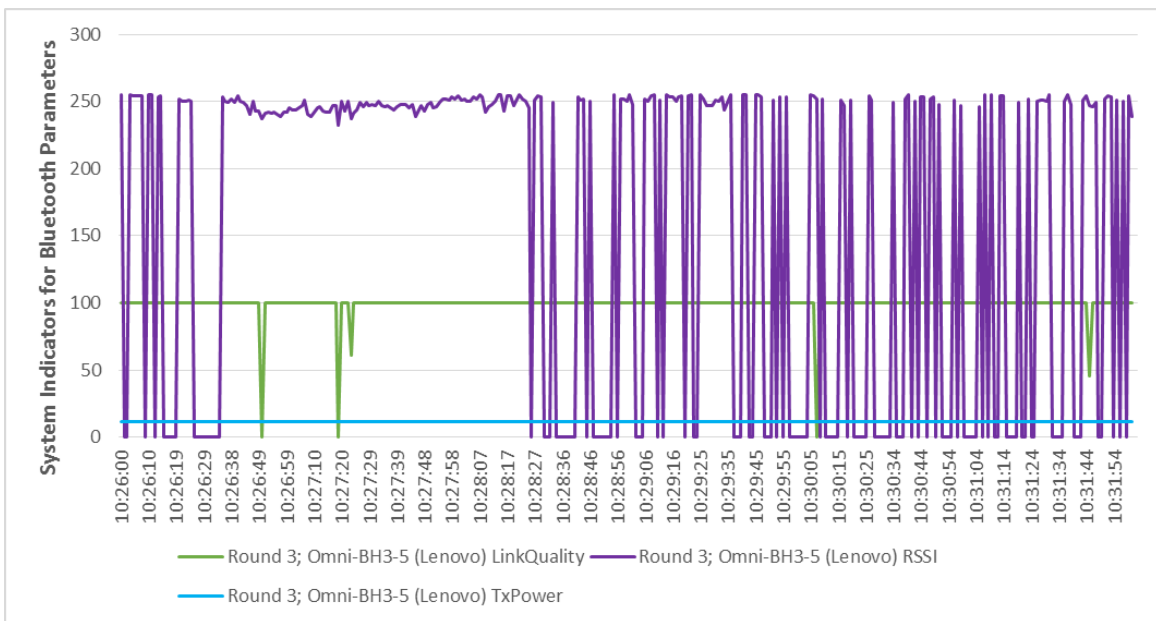
(3) Bluetooth Connection

In an attempt to explain poor throughput, the researchers looked into the Bluetooth network parameters on each of the sensors as well as on the Omni receiver. Two computers were used during this test, a Lenovo and a MacBook. The figures 52 through 55 depict the values for link quality, RSSI, and TX power for each of the test rounds. In general, link quality values range from 0 to 255, with 255 indicating an invalid value, a link down. The RSSI values range from 0 to 254 with 128 being an invalid indicator, link down. The transmit power values range from -30 to 20, with -128 being an invalid indicator. Throughout the three

rounds depicted below, the transmit power remained constant, at 12, indicating a constant transmit mode in all the three cases.

Figure 52 depicts Bluetooth parameters from the OmniSense application during round 3 of the one sensor phase testing with Lenovo. It is shown that the connection was established during the round 3 testing. However, although the TX power remained constant (at 12), the RSSI and link quality indicate intermittent connectivity. During this time the RSSI link was down 37.1%, while the connection (link) was down 0.9% of the time.

Figure 52. Phase 1: Omni data from Lenovo: Bluetooth connection with BH3-5 during one sensor bench testing



Figures 53 and 54 depict the Bluetooth parameters from the OmniSense application during round 4 of the two sensor Phase testing with Lenovo. The figures show that the connection was established during the round 4 testing between Lenovo and BH3-5 (Figure 53) and BH3-1 (Figure 54). As in a previous round, the TX power remained constant. For BH3 sensor 5, the link quality data was not available and the RSSI was down 15.6% of the time. The link quality indicated connectivity issues with RSSI being down 37.1% and link down 0.9% of

the time. While the link quality parameter data was available for BH3 sensor 1, the data for RSSI and TX power indicated an invalid value of 128. According to the link quality data, there were interruptions in connection 3.2% of the time.

Figure 53. Phase 1: Omni data from Lenovo: Bluetooth connection with BH3-5 during two sensor bench testing

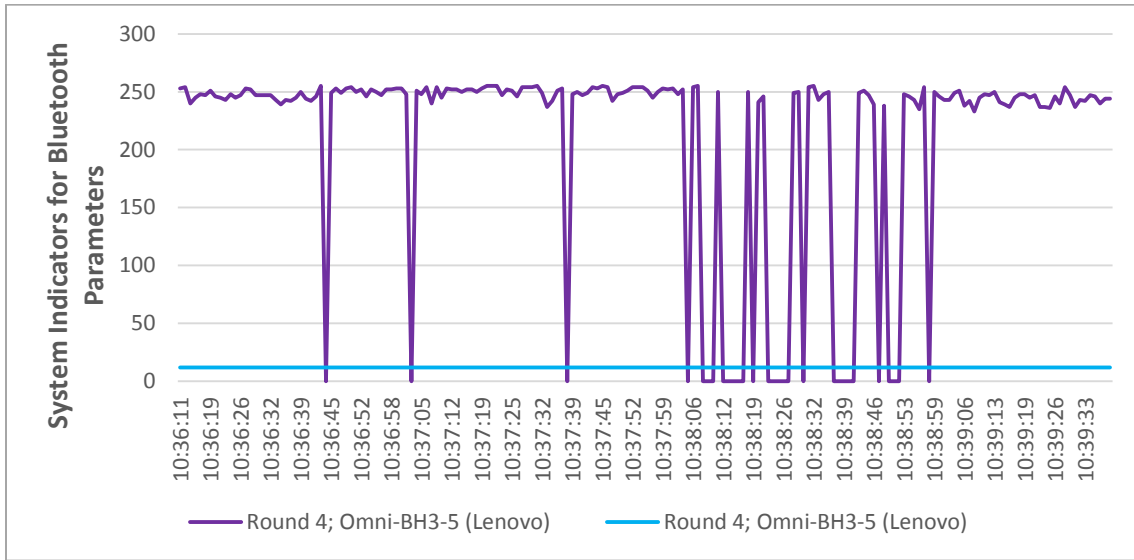


Figure 54. Phase 1: Omni data from Lenovo: Bluetooth connection with BH3-1 during two sensor bench testing

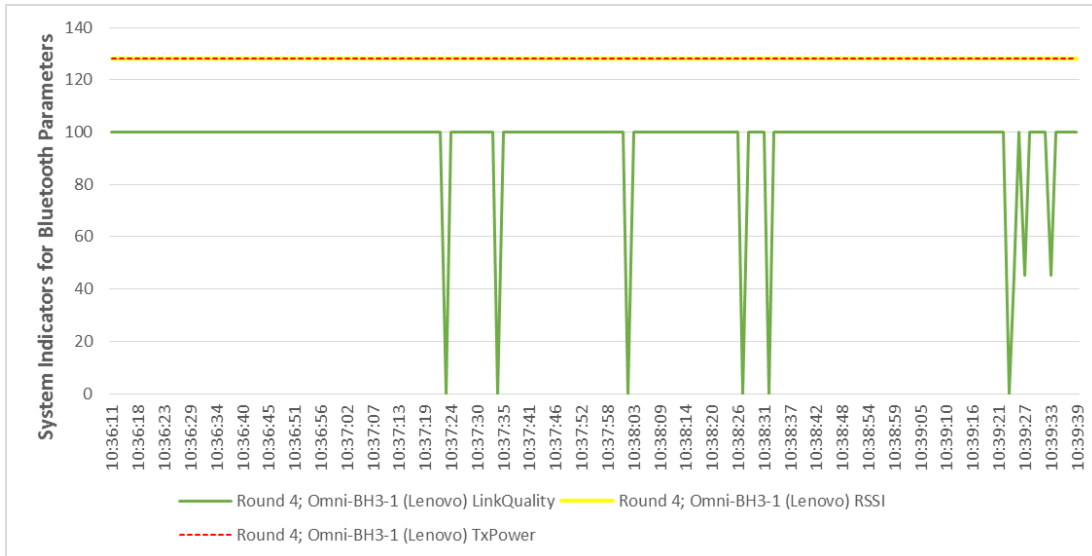


Figure 55 depicts the Bluetooth parameters data for MacBook's connection with the two sensors, BH3-1 and BH3-5, during the two-sensor baseline testing of this phase. The link quality data for the first sensor (BH3-1) was not available. In addition, both RSSI and TX Power indicated an invalid value. The second sensor (BH3-5) had a link quality of 100, indicating that connection between the Omni receiver and the BH3-5 was established. The transmit power was continuous. However, the RSSI was intermittent with only 86% of the time being in a receive mode.

Figure 55. Phase 1: Omni data from MacBook: Bluetooth connection with BH3-1 and BH3-5 during two sensor bench testing



The data showed that throughput was slightly higher and the RSSI had less connectivity drops with the two sensor test on Lenovo versus the two-sensor test on a MacBook. The OmniSense application is not compatible with a MacBook. Therefore, the virtual machine was used to capture data. This may have contributed to some missing and invalid values as well as low throughput.

It appears that overall, on average, the throughput for SIM-G and SIM-P is worse than the throughput for BH3 sensors. Unless, the BH3 sensor is being worn at the same time as the SIM sensors and BH3 is transmitting data via ECHO.

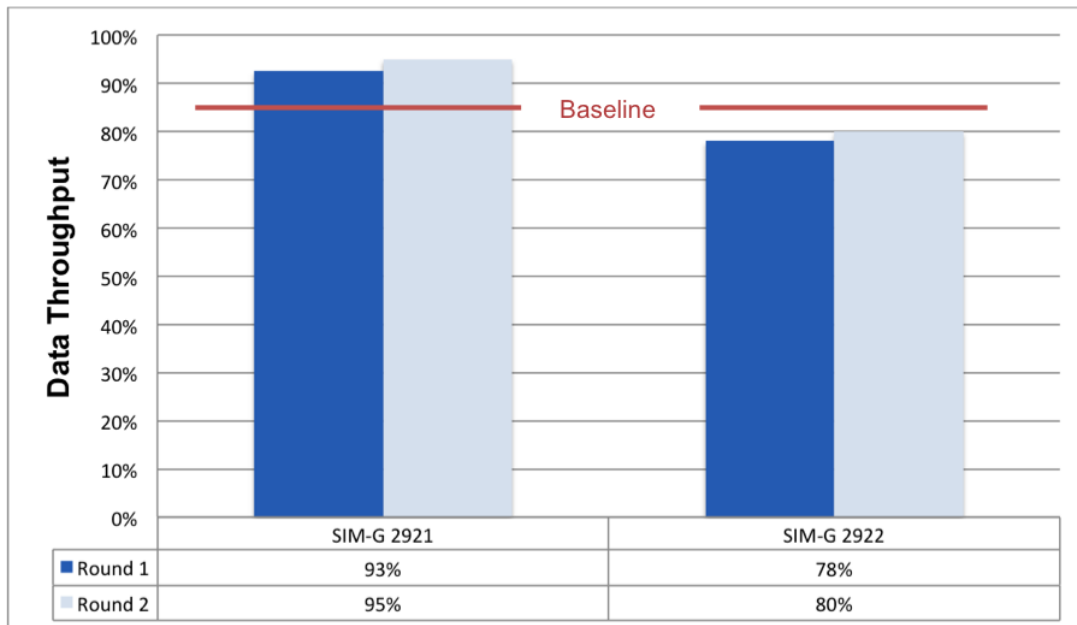
b. *Triax SIM-G and SIM-P*

The peak linear acceleration (PLA) is the Triax SIM-G and SIM-P sensors' primary measurement that is pertinent to a remote healthcare professional. Measured in g-forces, this data provide information that can inform concussion diagnosis as well as provide insight into mode of injury.

(1) SIM-G Throughput Baseline

The researchers calculated data throughput by comparing SKYi registered impacts to actual impacts conducted on the SIM-G sensors. There were two separate rounds of testing conducted with the SIM-G (2921) and SIM-G (2922) sensors (Figure 56). The researchers calculated an average baseline of 94% and 79% for the respective sensors.

Figure 56. Phase 1: Triax SIM-G data throughput

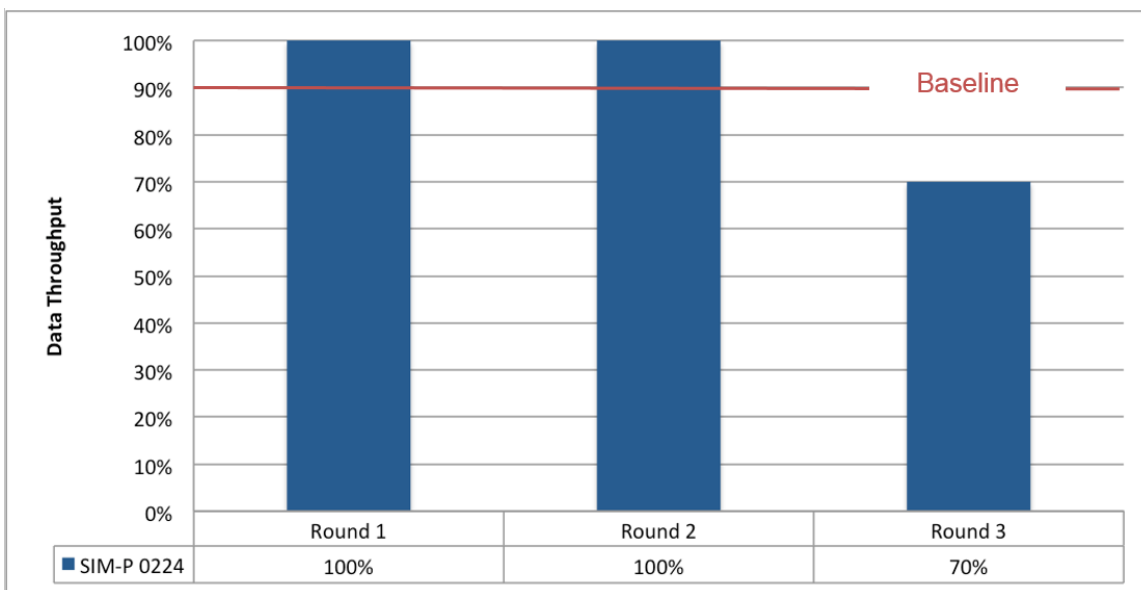


In order to establish a tighter concordance for baseline, the researchers aggregated raw data by the respective sensor across both rounds. A throughput of 84.4% and 85% for the respective sensors was calculated. This prompted the researchers to assume an 85% baseline for data throughput.

(2) SIM-P Throughput Baseline

The researchers conducted three rounds of 20 impacts to the SIM-P sensor (0224). A data throughput of 100%, 100%, and 70% were respectively recorded (Figure 57).

Figure 57. Phase 1: Triax SIM-P data throughput

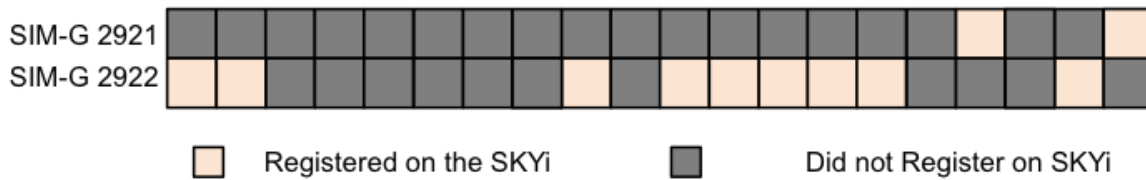


The researchers concluded that the third observation was possibly due to variance in testing, but agreed to not discount that round of testing and assumed a 90% impact registration rate for throughput as a baseline.

(3) SIM-G Signal Contention for Data Throughput

After a round of 20 simultaneous impacts on both SIM-G sensors it was found that only one sensor registered on the SKYi per synchronized impact. Additionally, as presented in Figure 58, it was noted that of the 40 combined impacts conducted on the sensors, only 11 impacts registered on the SKYi. Ten percent of impact that were conducted on the 2921 sensor and 45% of impacts conducted on the 2922 sensor.

Figure 58. Phase 1: 20 simultaneous impacts administered to two SIM-G sensors



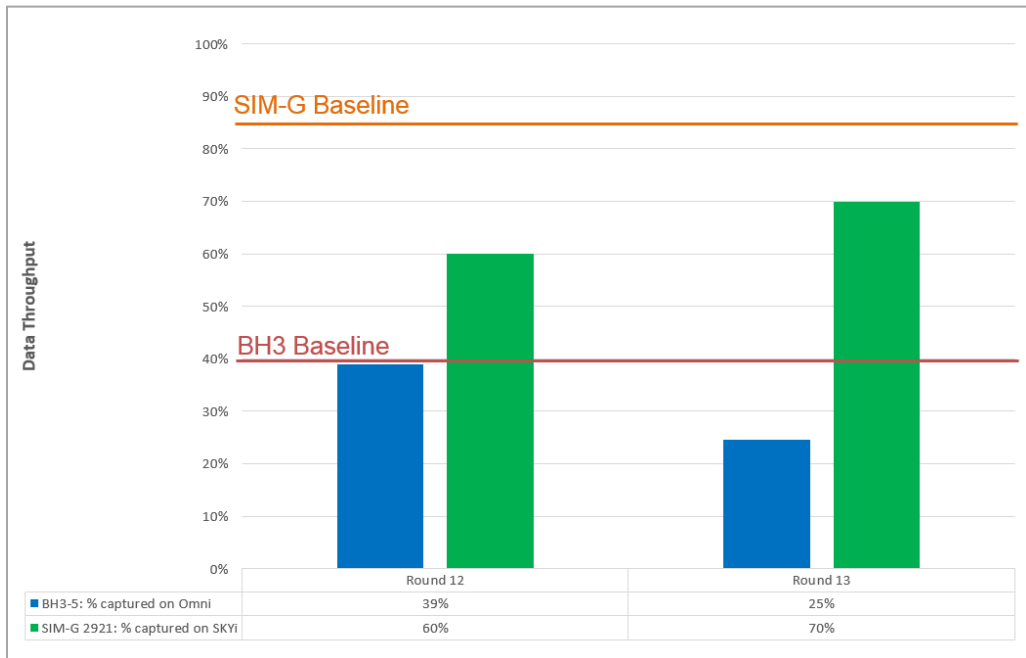
(4) SIM-P Signal Contention for Data Throughput

In order to test for potential interference from another proximal SIM-P sensor, the researchers conducted similar simultaneous impact experiments as on the SIM-G sensors. Based on the recorded impacts, the researchers observed that no sensor interference was exhibited. One-hundred percent of the two rounds of 20 simultaneous impacts registered on both sensors.

(5) BioHarness 3 and Triax SIM-G Sensor Testing

During the last two rounds of Phase 1 researchers conducted multiple sensor testing with BH3 and SIM-G sensors. The overall data throughput was higher for the SIM-G sensor than the BH3 sensor by 21% and 45.4% in rounds 12 and 13, respectively (Figure 59).

Figure 59. Phase 1: data throughput for simultaneous test of BH3 and SIM-G sensors



However, the BH3 sensor outperformed the SIM-G sensor in respect to the previously established baseline. Based on the data throughput baseline of 39.5% for BH3 and 85% for SIM-G, the BH3 was closer to its baseline by an average of 7.7% while the SIM-G was away from its baseline by an average of 20%.

2. Data Utility and Data Accuracy

The researchers found data disparities between the sensor (data originator) and the acquiring node (data receiver) during throughput baselining. As the result of this discovery, they expanded the focus of their research to include the data accuracy factor from the system quality dimension.

Data utility (DU) is a subset of data accuracy (DA), with the caveat that DU only focuses on DA for end user pertinent data. From the perspective of a healthcare provider these are health measurements. Specifically, in the context

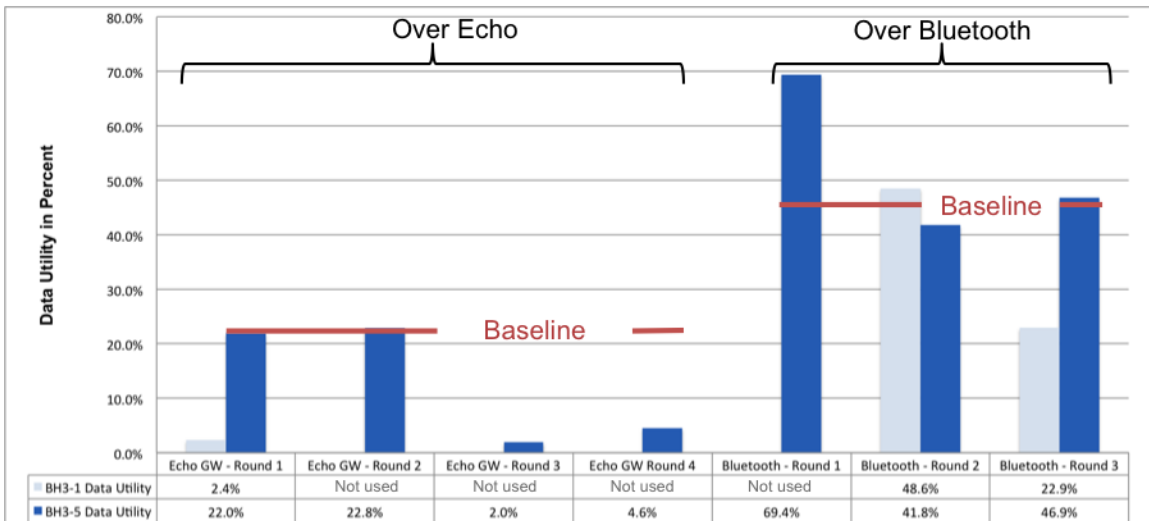
of this research and the sensors involved, these are heart rate, breathing rate, posture, activity, and peak linear acceleration.

a. Data Utility: Zephyr BioHarness 3 Sensor

The researchers conducted a four-point query match of data that were received on the acquiring node with data that were recorded on the BH3 sensor. The data were then further refined to eliminate any duplicates by ensuring that each measurement timestamp was unique.

Over the seven rounds of testing conducted in the Phase 1 experiments, the researchers observed that DU ranged from 2.4% to 69%. The DU metrics for these rounds were grouped by data capture protocol (Figure 60).

Figure 60. Phase 1: data utility with corresponding data utility rates baseline for ECHO and Bluetooth



The researchers observed that there were significant variances in DU rates between rounds 1–2 and rounds 3–4 when transmitting data over ECHO gateway. While the researchers introduced Triax sensor signal contention in 2.4 GHz to the environment during Rounds 3–4, they were not able to attribute this low DU ratio to signal contention alone. A further review of these rounds’ data

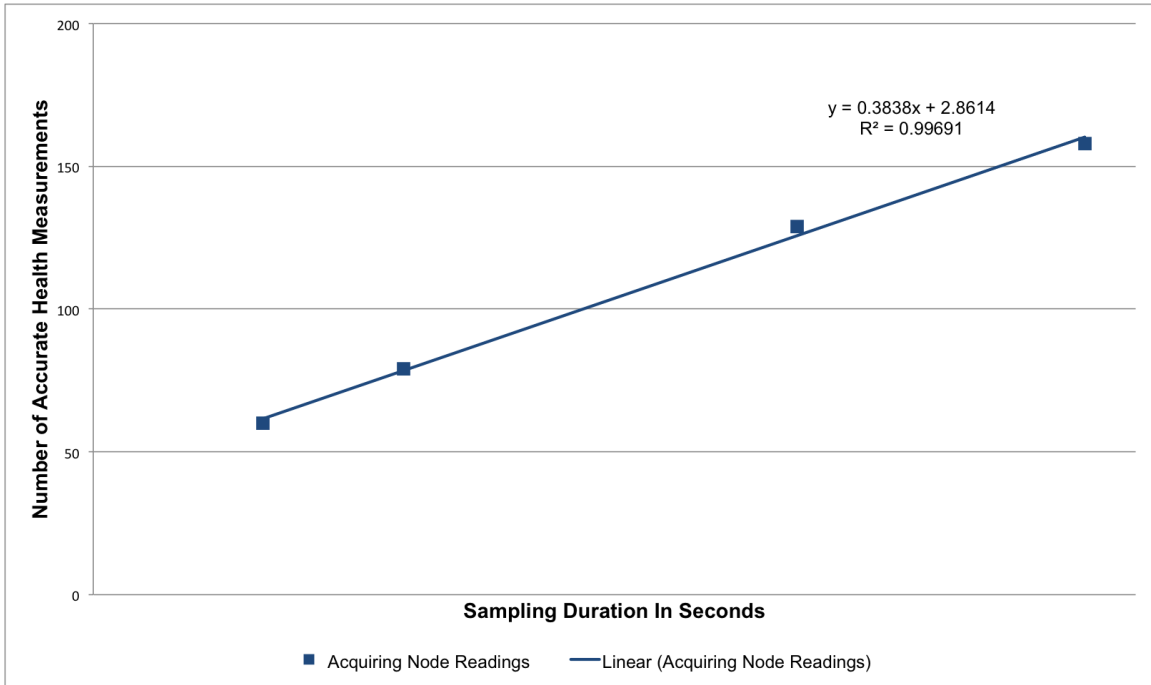
presented in Table 9 showed that the sampling duration was much lower for rounds 3–4 than for rounds 1–2.

Table 9. Phase 1: raw data used to calculate data utility for ECHO rounds

ECHO Round	1	2	3	4
Sampling Duration in Seconds	410	320	153	197
Accurate Measurements Captured on Acquiring Node	158	129	60	79

The researchers further conducted a regression of accurate health data measurements on sampling duration and found a strong correlation with an $R^2 = 0.99691$ (Figure 61). The researchers concluded that the calculated DU ratios for rounds 3–4 were comparatively low due to the sampling duration. Consequently, the researchers used rounds 1–2 to baseline the data utility ratio of 22.4% for sensors connected via ECHO gateway.

Figure 61. Phase 1: linear regression of accurate health data measurements on sampling duration



The researchers conducted a review of the calculated DUs from the Bluetooth rounds and averaged a DU ratio of 45.9% as a baseline for Bluetooth connected BH3 sensors. The researchers noted that data utility was significantly higher for data captured over Bluetooth than for data captured over ECHO gateway. Specifically, when looking at Round 1 for the respective protocols, it was noted that DU over Bluetooth was three times better.

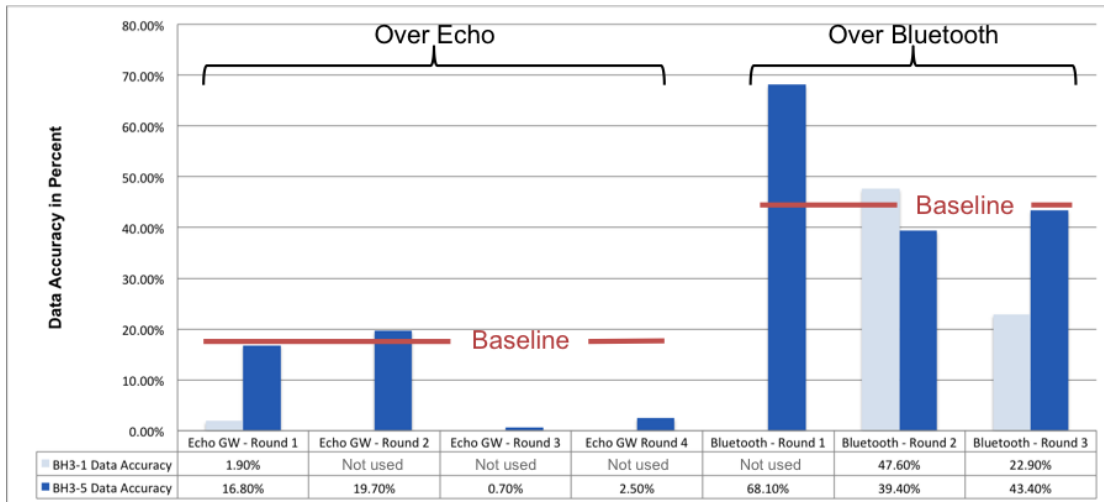
In conducting a review of these two rounds, it was found that the sampling periods were 5.3 minutes and 6 minutes, respectively. As previously presented, sampling duration has a direct impact on the number of accurate health readings. Consequently, the researchers reduced the Bluetooth Round 1 sampling period by randomly selecting 320 measurements (the equivalent of 5.3 minutes) to equalize the two rounds. In turn, the researchers calculated a modified DU of 69.7%, which is 1.73 times more efficient than observed for the same sampling duration over ECHO. This observation was corroborated by a 1.78 calculated efficiency using the y-slope equation from Figure 57.

b. Data Accuracy: Zephyr BioHarness 3 Sensor

The researchers conducted an eight-point query match of data that were received on the acquiring node with data that were recorded on the BH3 sensor. These included the four health measurements as well as four sensor status measurements. The resulting queries were further refined to eliminate any duplicates by ensuring that the timestamp of each measurement was unique.

Upon reviewing the data, the researchers found that DA ranged from 0.7% to 68.1% (Figure 62). The researchers observed similar trends as presented in the previous section and therefore applied the same rationale at calculating the DA baseline.

Figure 62. Phase 1: data accuracy rates with corresponding baseline for ECHO and Bluetooth



For BH3 sensors that were connected via ECHO gateway, the researchers determined the baseline of 18.3%. Similarly, the baseline of 44.3% was determined for BH3 sensors connected via Bluetooth to the receiver node. These baselines were used in the follow-on phases to further evaluate the BH3 and SIM sensors.

c. *Triax SIM-G and SIM-P Sensors*

Unlike the BH3 sensor, it is not possible to download data directly from the Triax sensors. Consequently, data utility and data accuracy baselines are informed by the data throughput baselines that were established in previous sections. These rates are 85% and 90% respectively for the SIM-G and SIM-P sensors.

3. Maximal Link Distance

Maximal link distance was not tested during Phase 1 testing. However, baseline benchmarks for this criterion was established during Phase 2 testing.

4. Reachback

Currently, there is no automated means to transmit data from the OmniSense application or the Triax SIM-P solutions to the Cloud-based data repository or a user of choice via an Application Programming Interface. A user would have to manually export logs from the systems and then send these logs containing health status data to a required destination. To possibly mitigate this issue, the researchers reviewed third-party Android applications that were marketed to work with the BH3 sensors.

(1) Android Application Reachback Test

During the test of Android applications for BH3 synchronization, data capture, and data extracting, several observations became evident. First, some of the Android applications are Android version dependent. The researchers were not successful in installing the Zephyr application for BH3 sensors on the Pantech. However, the researchers were successful in installing the Zephyr application on Google Nexus 7 tablet and synchronizing one of the BH3 sensors with the application. However, this presented a new challenge. The challenge is a master-slave relationship between a sensor and an application with which this sensor is synchronized. Once BH3 sensor was synchronized with the Zephyr application on the Google tablet, this particular sensor would no longer

communicate with the OmniSense application. Furthermore, while the BH3 data was visible live on the Zephyr application, the data could not be extracted for future use. Upon completion of testing BH3 sensors with Android applications, the researchers concluded that marketed capabilities were not able to produce the desired results of transmitting BH3 data to a Cloud-based solution.

(2) SIM-G Reachback

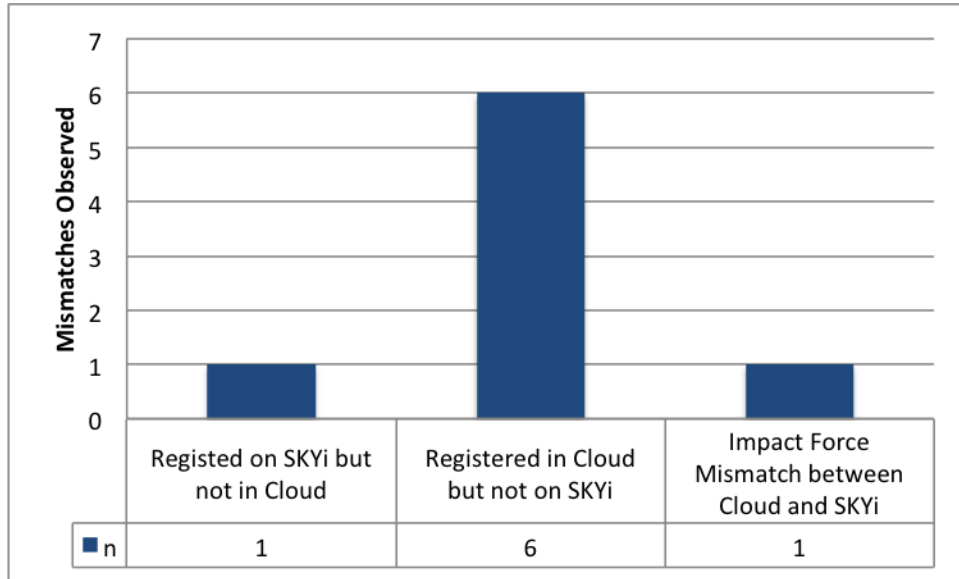
In contrast to the BH3 and SIM-P's lack of reachback capabilities, the SIM-G does offer a Cloud-based application to track impact data. The SIM-G impact data are transmitted via the SKYi to the Triax Cloud application where data can be visualized. While this solution is a step forward in fusing data into an Electronic Health Record application, it is not a fully interoperable solution.

(3) SIM-G SKYi and Triax Cloud

According to vendor specifications (T. Hollingsworth, personal communication, 2016), all impact data received on the SKYi receiver are transmitted via 802.11 to the Triax Cloud (the Cloud). The researchers compared the data in the Cloud to data retained on the SKYi receiver. Specifically, the researchers assessed PLA in g-forces and the corresponding timestamps recorded in both locations.

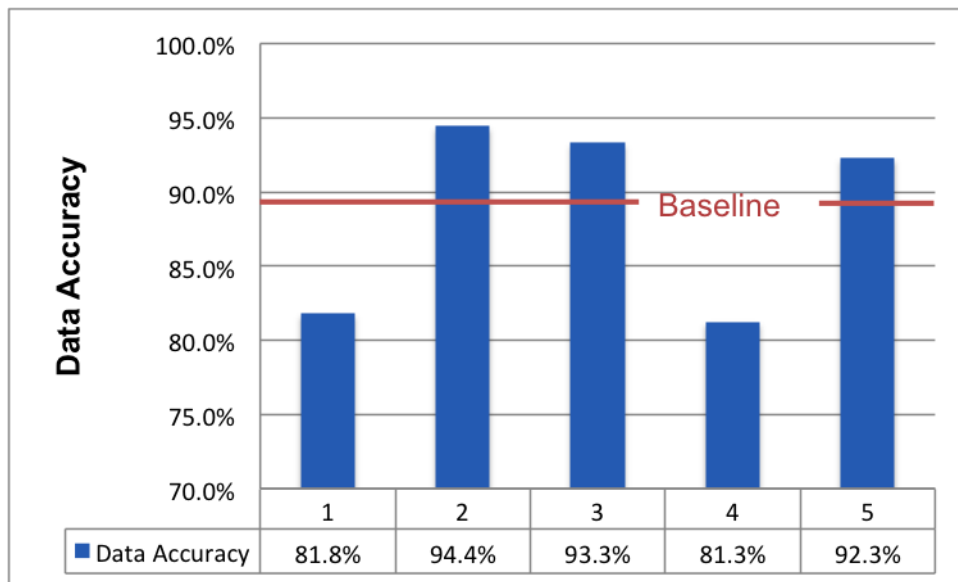
The researchers observed that there were instances of discordant data between what the SKYi registered and what was recorded in the Cloud. As presented in Figure 63, the preponderance of mismatches was due to data that was recorded in the Cloud but did not register on the sensor receiver. However, the researchers asserted that the Cloud data are valid as impacts were conducted during the recorded timeframes.

Figure 63. Phase 1: observed instances of Cloud and SKYi data discordance



The researchers calculated data accuracy rates that ranged between 81.2% and 94.4% for the five sets of experiments that exhibited discordance (Figure 64).

Figure 64. Phase 1: data accuracy rates for SKYi experiments exhibiting data discordance



As an outcome of this analysis, the researchers determined the average data accuracy rate of 89% as an acceptable reachback baseline for subsequent experiment phases.

5. Additional Discoveries

While conducting Phase 1 experimentation, the researchers captured findings that were not part of the original evaluation objectives. These additional discoveries were found to be nonetheless germane to the research conducted and have been included here. Specifically, these discoveries provide observations on software application effectiveness as well as time synchronization and measurement disparities among sensors.

(1) BioHarness 3 versus Omni Application

On several occasions the OmniSense application would lose a previously established connection with BH3 sensors. During Phase 1, BH3 sensors were on and worn by the researchers continuously for approximately 4.25 hours. However, during this time, the Omni application would occasionally lose the connection and display a “Device Not Worn” message (Figure 65). Figure 66 depicts the “No Error” message when the Omni application would re-established a connection to a BH3 sensor.

Figure 65. Phase 1: “Device Not Worn” message from the OmniSense application

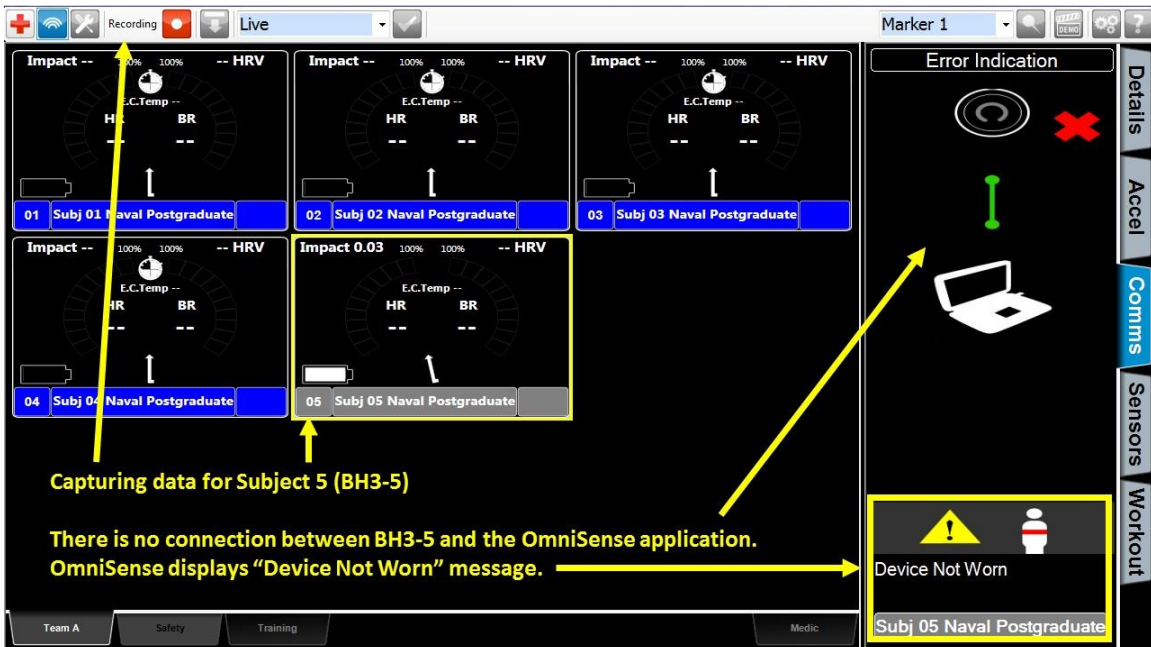
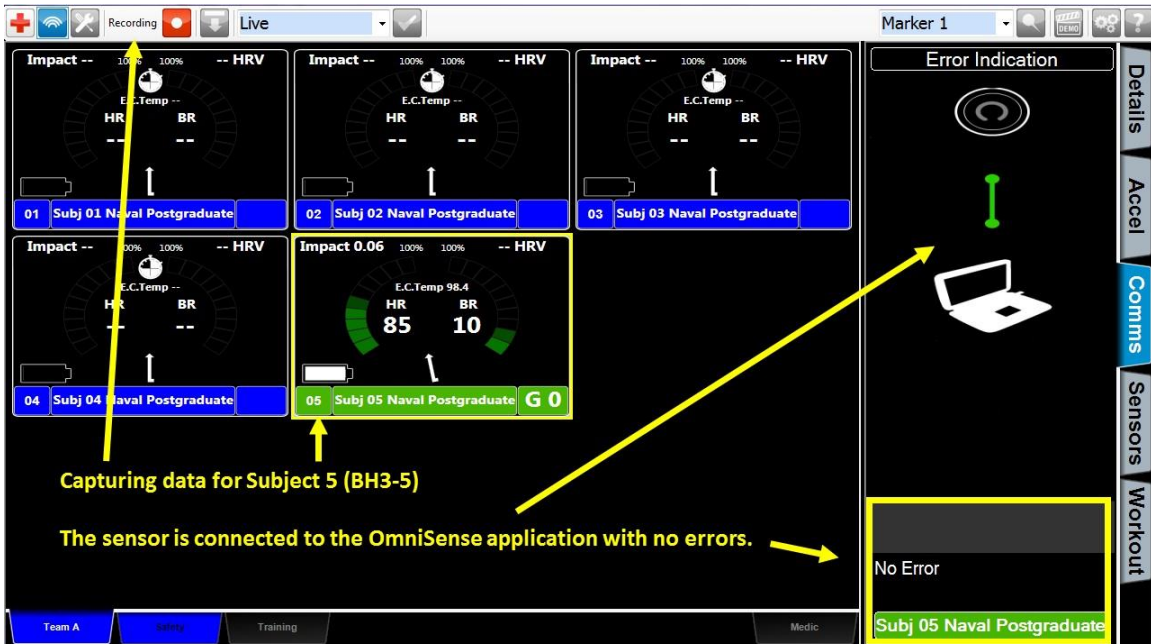


Figure 66. Phase 1: sensor connected to the OmniSense application

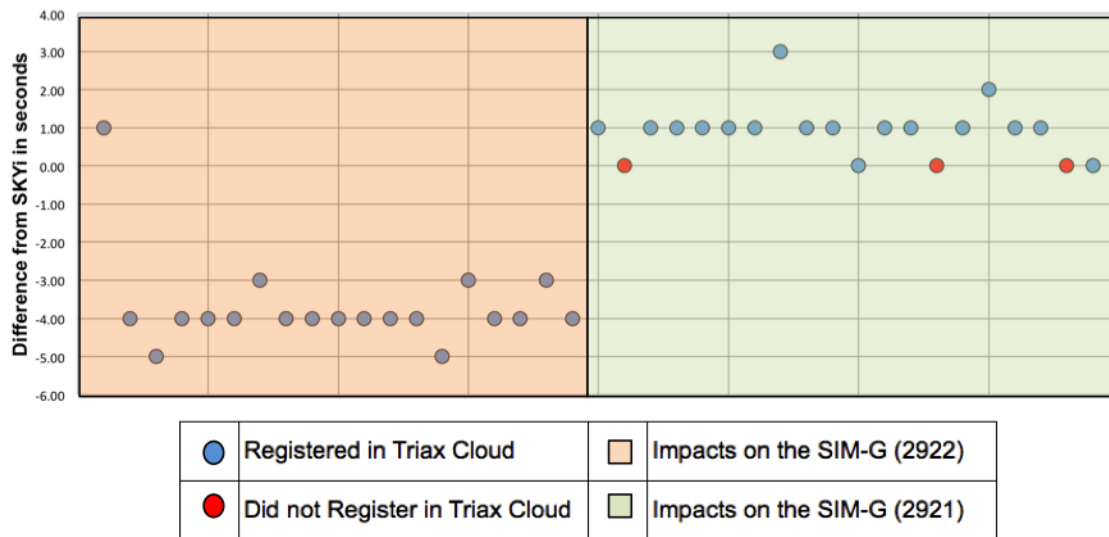


The researchers were not able to identify the source of this intermittent connection loss between sensors and the OmniSense application.

(2) SIM-G SKY-i and Triax Cloud Timestamp Synchronization

The researchers noted that there were timestamp synchronization disparities between what the SKYi device registered and what the Triax Cloud logged for a corresponding impact. Specifically, as presented in Figure 67, 95% of the impacts administered to the SIM-G 2922 sensor registered in the Cloud chronologically earlier than the impacts recorded on the SKYi (mode = 4 seconds). This was contrasted by the impacts administered to the SIM-G 2921 sensor, where impacts were recorded with a one second delay in the cloud.

Figure 67. Phase 1: timestamp variation between SKYi and Triax Cloud



(3) Variation in Peak Linear Acceleration between SIM-P and SIM-G

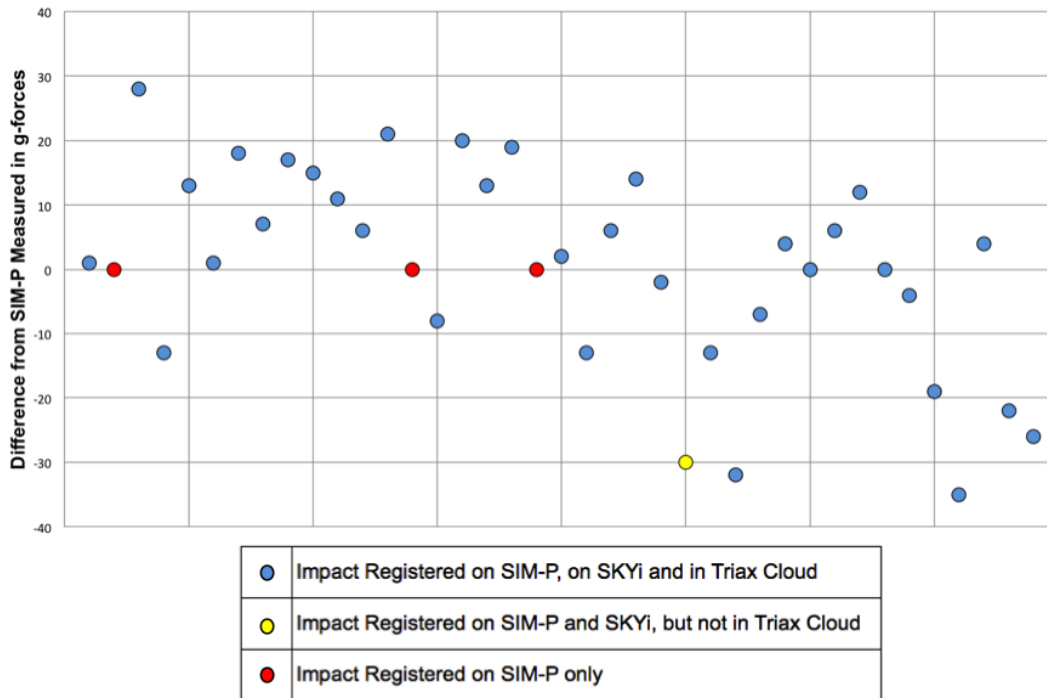
In order to introduce a type of control into the testing environment, the researchers conducted impact testing with both the SIM-P 0224 and SIM-G 2921 sensors cupped in the same hand. In selecting a control for comparison between the two sensors, the researchers opted for the SIM-P. This decision was made

due to the SIM-P's ability to record impacts in long-term memory, which the SIM-G currently does not have. Per vendor specification, the SKYi receiver should store up to 150 impacts in its memory. However, the researchers did not observe this specification during their test.

After the test, the researchers observed that out of the 40 administered impacts, 100% were recorded on the control sensor while only 92.5% registered on the SKYi. Additionally, it was found that only 36 of the 37 (97%) impacts that registered on the SKYi were recorded in the Cloud.

When assessing the variation in peak linear acceleration between the SIM-P and SIM-G sensors, the researchers observed that there was preponderance (22/40) in higher g-force recordings on the SIM-G over the SIM-P (Figure 68). Due to the means of impact testing and how the sensors were held (the SIM-G closer to the palm while the SIM-P resided directly on the SIM-G), the researchers ascribed a possible loss of kinetic force that was absorbed in the SIM-G before being transmitted on to the SIM-P sensor.¹

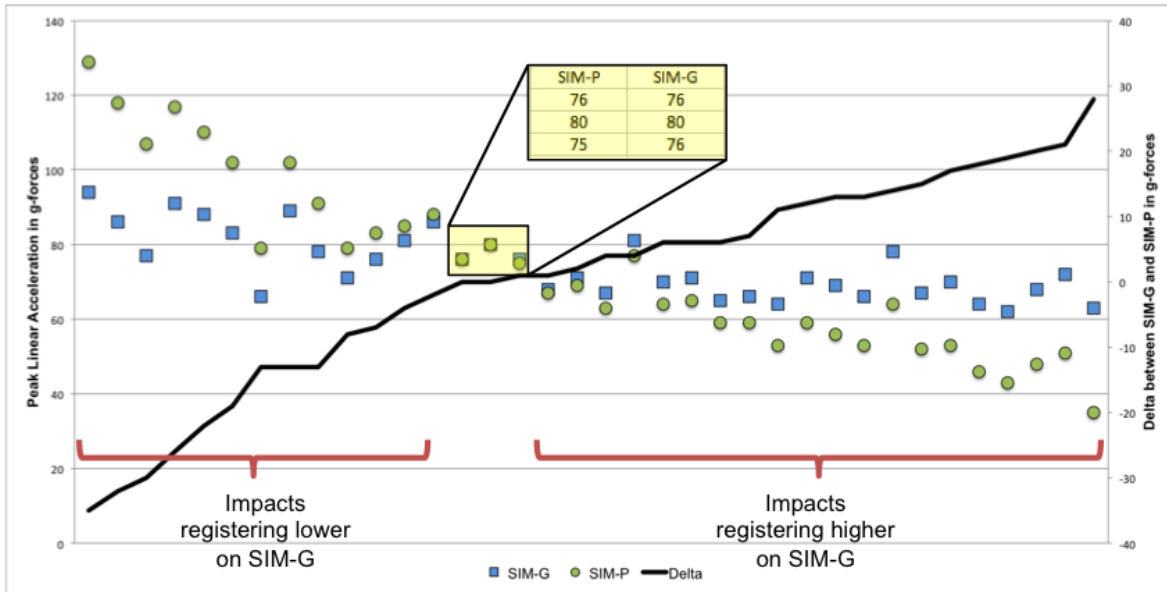
Figure 68. Phase 1: variation in g-forces registered on SIM-G when compared to SIM-P



¹ Positive numbers signify a higher PLA registered on the SIM-G while negative numbers signify the reverse.

Further review of the data, as presented in Figure 69, suggested that there may be a tight concordance of PLA registered on both sensors at between 75 and 80 g-forces (see callout in Figure 69). The data also suggested that there is a general tendency for the SIM-G sensor to register a lower PLA above 80 g-forces, while simultaneously registering a higher PLA when impact forces are less than 69 g-forces.

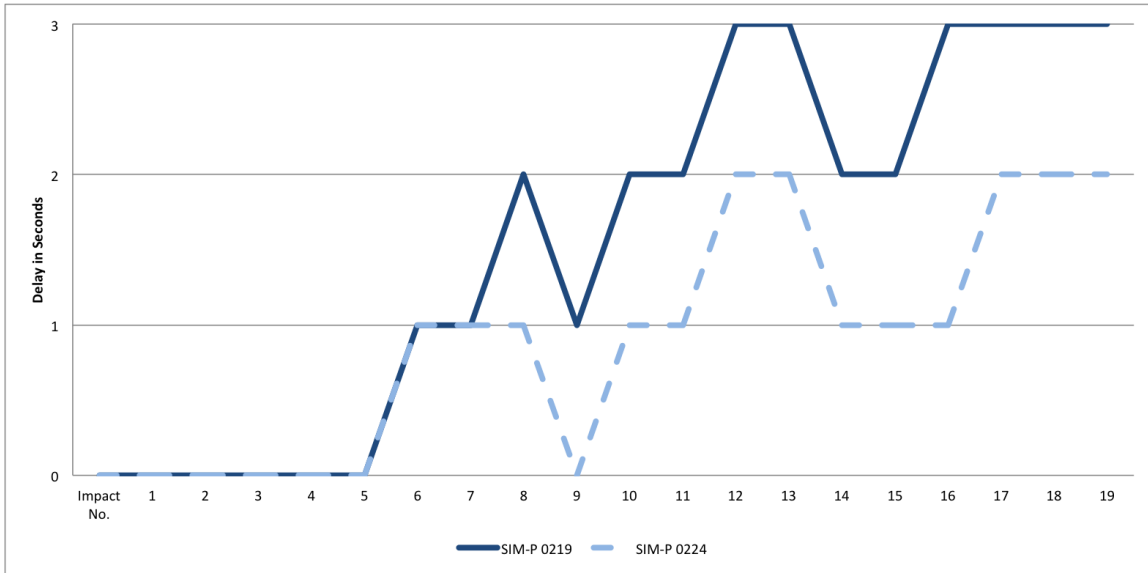
Figure 69. Phase 1: comparative visualization of g-forces registered on the SIM-P and SIM-G sensors



(4) Timestamp Slippage

The researchers noted a rising delay in the registered timestamp as the data throughput sub-experiment progressed. As presented in Figure 70, the SIM-P 0219 sensor and the SIM-P 0224 sensor exhibited a timestamp delay range of 0–3 seconds and 0–2 seconds, respectively.

Figure 70. Phase 1: timestamp delay increases over 20 impacts simultaneously administered to the SIM-P sensors



This was an additional finding. The researchers postulate that with more impacts coming over time, the Triax system starts to experience the compounding timestamp delays.

6. Findings Summary

Table 10 provides a summary of Phase 1 findings based on the evaluation criteria. Based on the testing environment and tests performed, the researchers established that the rates in Phase 1 will serve as baselines for subsequent phases. The BH3 sensor has different percentages for the throughput, data utility, and data accuracy due to BH3's ability to collect a variety of health measurements and hardware data. However, SIM-G and SIM-P sensors only collect data for peak linear acceleration. Due to the availability of only a single measurement, the SIM-G and SIM-P data throughput, data utility, and data accuracy are the same.

The researchers conducted Phase 1 testing in a control environment where all the equipment was placed within a diameter of one meter. Due to this

test criteria the maximal link distance was not tested, showing as “Not Tested” in the summary Table 10.

As previously stated, the BH3 and SIM-P do not have the capability to upload the health status data to a Cloud. Hence, “No reachback capability” appears under the Reachback factor in the summary Table 10. Throughput of 89.0% was established as a reachback baseline for the SIM-G sensor transmitting data to the Cloud via the SKYi receiver.

Table 10. Phase 1: findings summary table

Factor	Sensor	Protocol	Baseline
Data Throughput	BH3	ECHO	39.5%
		BT	90.1%
	SIM-G	85.0%	
		SIM-P	90.0%
Data Utility	BH3	ECHO	22.4%
		BT	45.9%
	SIM-G	85.0%	
		SIM-P	90.0%
Data Accuracy	BH3	ECHO	18.3%
		BT	44.3%
	SIM-G	85.0%	
		SIM-P	90.0%
Maximal Link Distance	BH3	ECHO	Not Tested
		BT	
	SIM-G	Not Tested	
		SIM-P	Not Tested
Reachback	BH3	ECHO	No reachback capability
		BT	
	SIM-G	89.0%	
	SIM-P	No reachback capability	

Additional findings, not included in the evaluation criteria, were noted during Phase 1. These findings include:

- BH3: Intermittent drops in connection between OmniSense and BH3 sensors within one meter of each other

- SKYi: Timestamp synchronization disparities between what the SKYi device registered and what the Triax Cloud logged for a corresponding impact
- SIM-G/SIM-P: Variations in registered SIM-G and SIM-P impacts based on peak linear acceleration (in g-force)
- SIM-P: Timestamps delays increased over 20 impacts conducted simultaneously to two SIM-P sensors

B. PHASE 2: SINGLE SENSOR TESTING

During this phase, the researchers performed two sets of tests, outlined in this section as Phase 2a and Phase 2b. In Phase 2a, the researchers present the data gathered during a bench test of BH3 sensors at the Monterey Fisherman’s Wharf (the wharf) and associated findings. Phase 2a consisted of five rounds. Table 11 provides the details of each round.

Table 11. Phase 2: test round descriptions

Round #	Start time	End Time	Description
Round 1	07:47:02	8:04:59	The circle (parking lot at the wharf): ~ Some areas are within line of sight (LOS) and some areas are out of LOS. ~ BH3-1 only worn on researcher one. ~ Using ECHO, a proprietary version of 802.15.4 protocol.
Round 2	08:08:00	08:16:16	The circle: Same as round one, but with an additional sensor. BH3-3 is placed in researcher one's trouser pocket.
Round 3	08:20:00	08:26:48	Straight line (parking lot at the wharf): ~ LOS straight line walk. ~ Add another sensor. BH3-5 is on and is placed in researcher one's jacket breast pocket. ~ Using ECHO, a proprietary version of 802.15.4 protocol.
Round 4	08:29:00	08:30:19	Attempt to use Bluetooth (parking lot at the wharf): ~ Same BH3 set up as round three, but using Bluetooth. ~ Ended this round at 6.5 meters due to frequent connection interruptions.
Round 5	08:42:00	09:00:26	The Pier (at the wharf): ~ Three sensors worn by researcher one. BH3-5 placement started in a jacket breast pocket down the pier and up in the hat down towards Del Monte Avenue. ~ Using ECHO, a proprietary version of 802.15.4 protocol.

Phase 2b provides the data and findings for the test of the Triax SIM-G and SIM-P sensors. Phase 2b consisted of two rounds. During both rounds, Researcher 1 walked up and down Via Del Pinar between Herrmann Drive and Via Del Rey in Monterey while Researchers 2 monitored the SKYi antenna at the intersection of Via Del Pinal and Herrmann Drive. During round one, the SKYi antenna was facing the sensor. During round 2, the SKYi antenna was facing away from the sensor. During this phase, the researcher' focus was on the maximal link distance of the SKYi antenna.

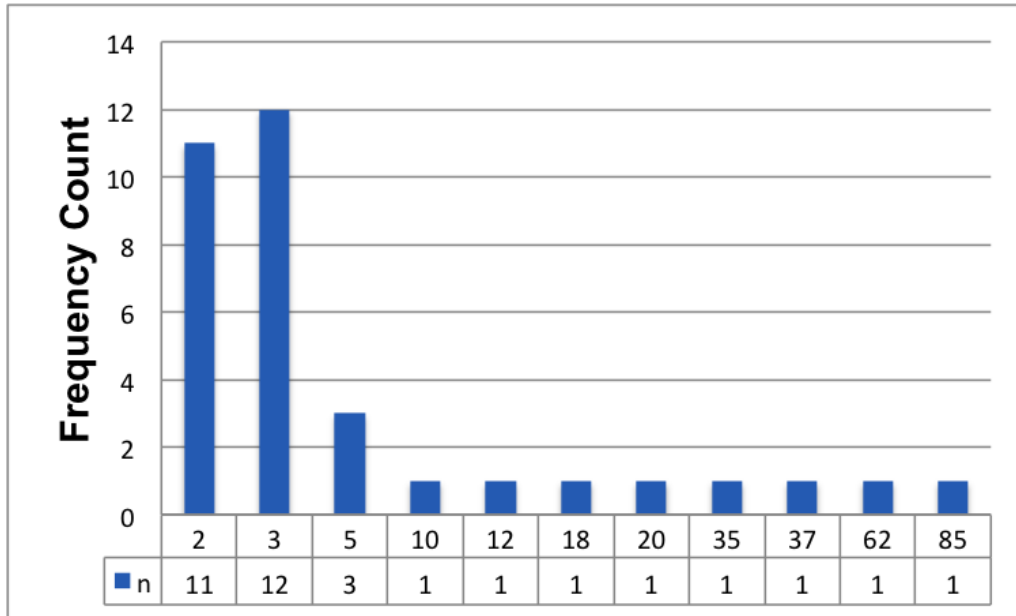
1. Phase 2a: BioHarness 3 Test

As in Phase 1, the researchers started their data analysis with the overall data throughput. Consequently, they proceeded to evaluate the BH3 data utility, data accuracy, and the maximal link distance. The values determined in this phase were established as benchmarks for follow-on phases.

a. Throughput

The researchers conducted a proxy analysis for data throughput by assessing the receive intervals on the acquiring node. During round 1, the researchers noted that the interval duration between measurements ranged from 2 to 85 seconds with 76.5% of these lasting five seconds or less (Figure 71).

Figure 71. Phase 2a: frequency count of interval length in seconds between recorded measurements



Since the BH3 sensor records a measurement set once every second, it is possible to make a relative assessment on data throughput from this data alone. Specifically, as presented in Table 12, it is possible to map throughput zones when coupled with GPS data (Figure 72). This representation is specific to round 1 of this phase.

Table 12. Phase 2a: throughput equivalents based on interval duration between measurements

Interval Duration (s)	2	3	5	10	12	18	20	35	37	62	85
Equivalent Throughput	50%	33%	20%	10%	8%	6%	5%	3%	3%	2%	1%
Zone Mapping											

Figure 72. Phase 2a: throughput zone mapping

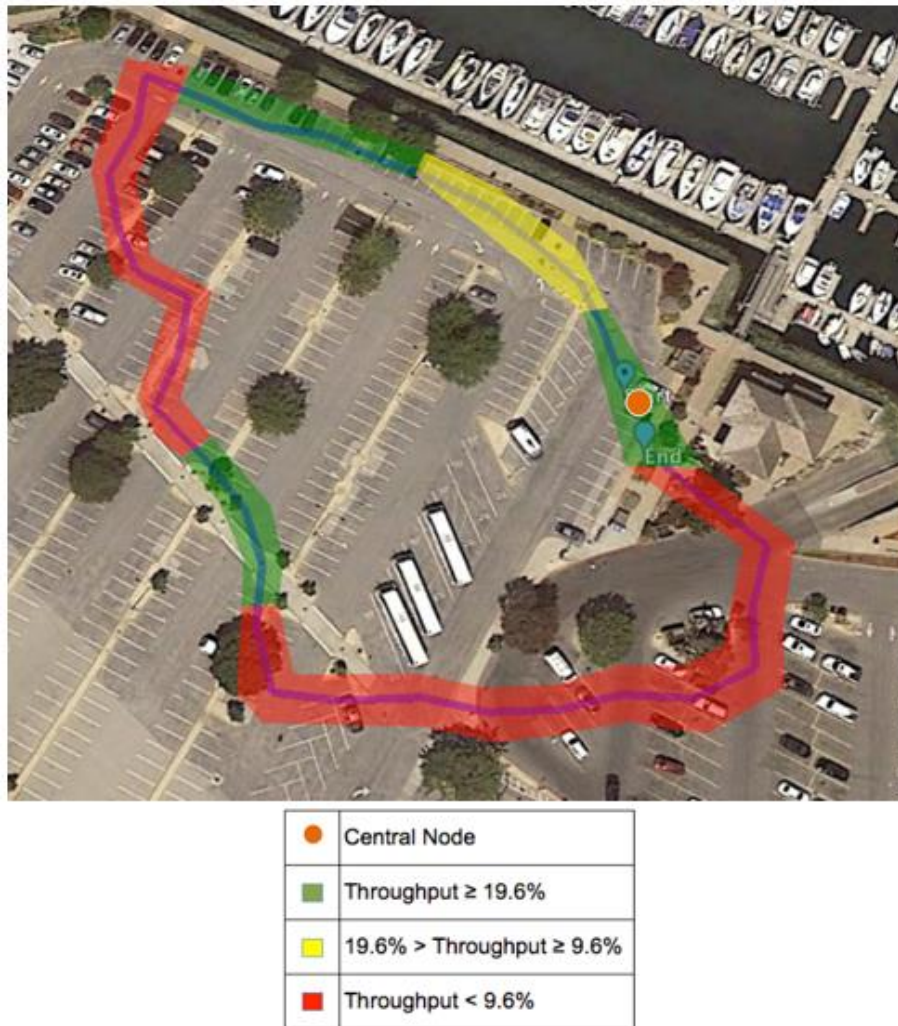
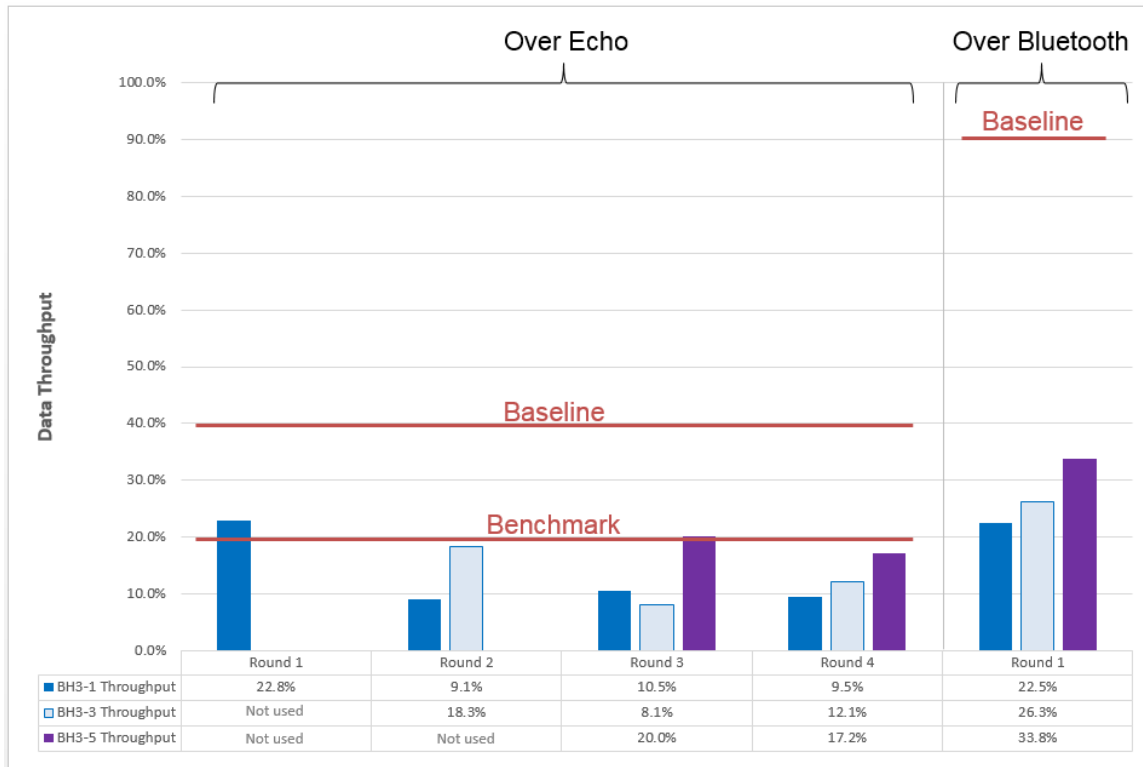


Figure 73 provides data throughput for all Phase 2a rounds. Data showed that data throughput was the highest when only one BH3 sensor (BH3-1) was connected to the OmniSense application. As more BH3 sensors were introduced into the Phase 2a experiment, the researchers observed a drop in data throughput anywhere from 12% to almost 65%. The researchers ascertained that this drop was due to a signal contention between the sensors.

Figure 73. Phase 2a: data throughput



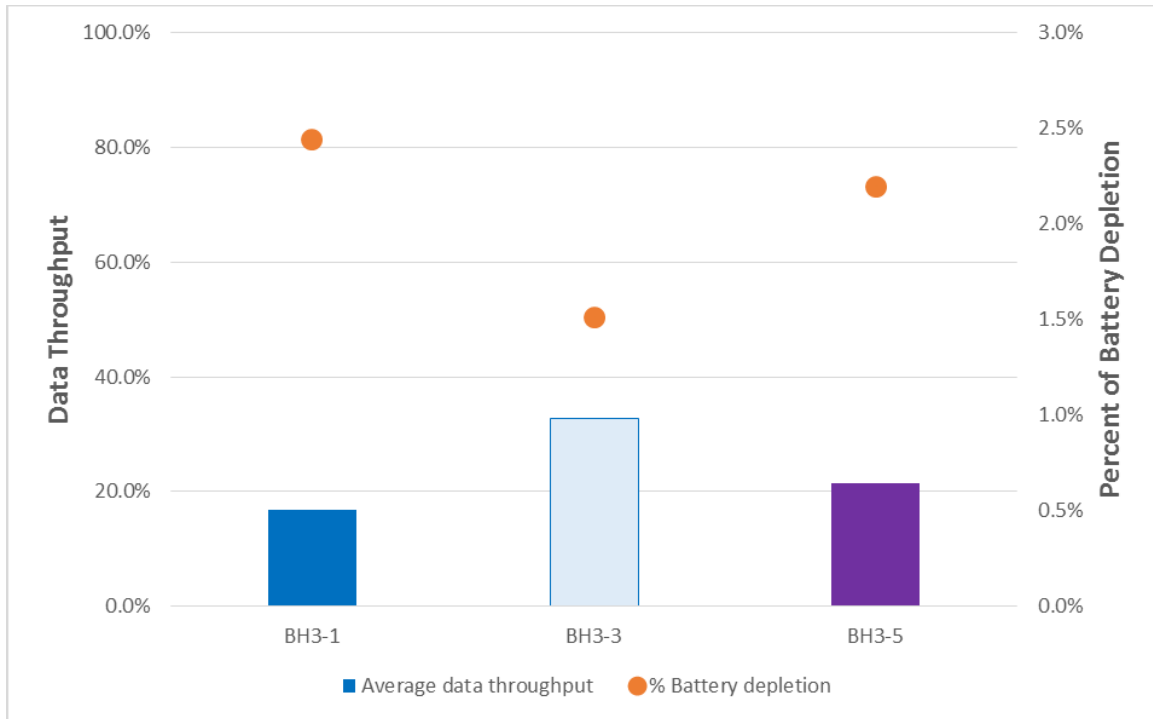
Upon review of data throughput for all the rounds, the researchers established 19.6% as the data throughput benchmark for follow-on experiments utilizing ECHO gateway. Although Bluetooth showed the highest level of throughput, the researchers decided to not proceed with Bluetooth testing or establish a benchmark for Bluetooth throughput. The researchers made this decision after an attempt to test connectivity via Bluetooth. Just 6.5 meters between the sensors and the OmniSense application, the OmniSense frequently lost connection with the sensors. According to OmniSense and BH3 Bluetooth parameters, the connection between sensors and the control node (the receiver) was down anywhere from 3.8% to 61.5%.

(1) Battery Voltage

While analyzing the battery voltage data, the researchers observed that the BH3 sensor with the highest data throughput had the least depleted battery.

In contrast, the BH3 with the lowest data throughput had the most depleted battery (Figure 74).

Figure 74. Phase 2a: BH3 data throughput versus percent of battery depletion



The researchers attributed this phenomenon to the issue of intermittent connectivity. The sensor with least amount of data transferred had to work harder to establish connectivity to transmit data, which depleted the battery faster. In contrast, the sensor with least connectivity issues had the most data transferred and the least battery depletion. The duration during which BH3 sensors were worn did not affect battery depletion.

b. Data Utility and Data Accuracy

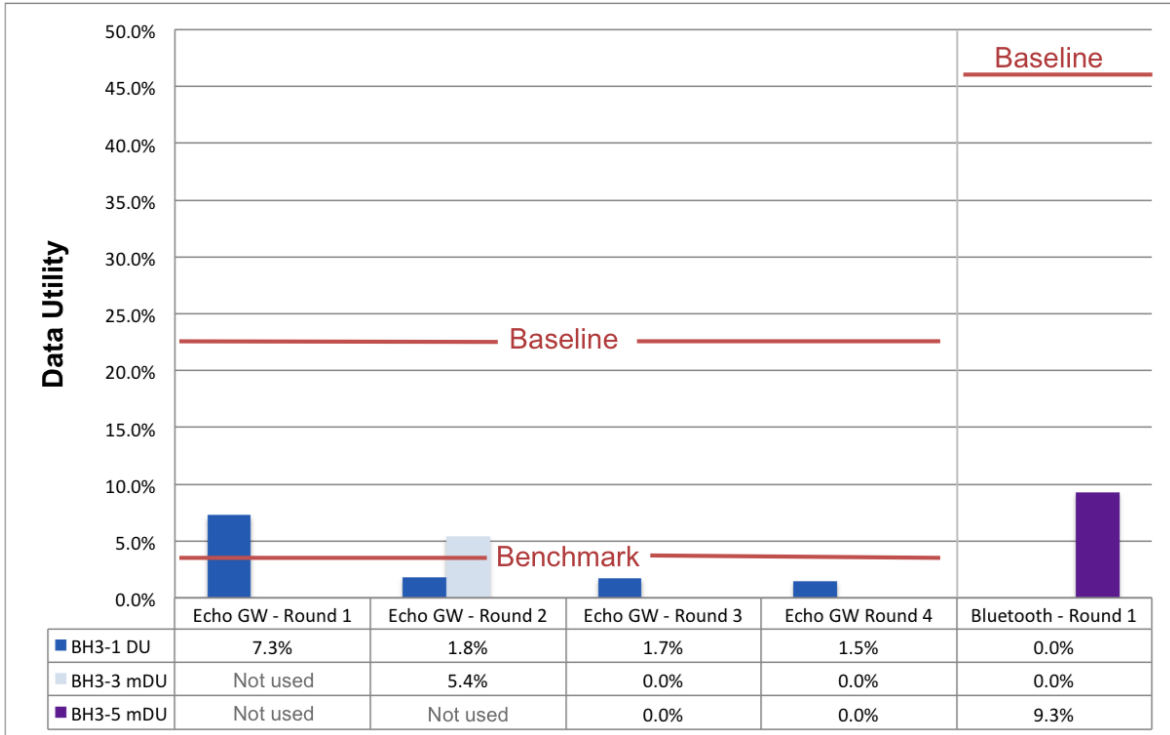
The researchers could only calculate DU and DA metrics in accordance with established analysis protocol on data received from the BH3-1 sensor. A review of the health measurements for breathing rate showed that the BH3-3 and

BH3-5 sensors recorded invalid values while the receiver node registered zero values for the same measurement set.

Despite this observation, it was first submitted that, since these sensors were used as controls, their data are still germane to informing a benchmark in this phase. Consequently, the researchers calculated a modified DU (mDU). They amended analysis protocol for the BH3 sensors by disregarding breathing rate values and substituting these with battery voltage values. To establish a modified DA (mDA), the researchers decided to rely on seven instead of eight matched data points.

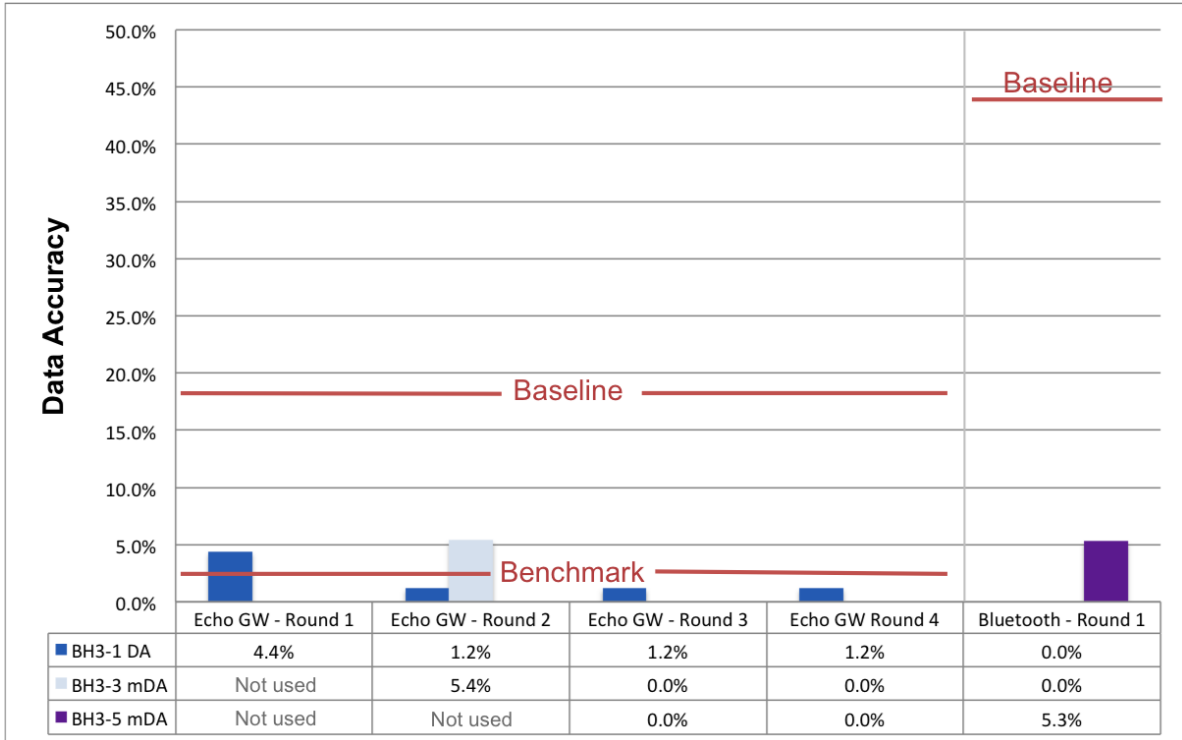
As a result of the modified protocol, the researchers established a DU benchmark of 4.7% for BH3 sensors over ECHO gateway (Figure 75). Following the rationale for not establishing a benchmark for BH3 data throughput over Bluetooth, the data utility benchmark was also not established.

Figure 75. Phase 2a: BH3 data utility ratios



The researchers observed an average DA of 2.6% over ECHO for this phase of testing, which was then selected as the DA benchmark for follow-on phases (Figure 76).

Figure 76. Phase 2a: BH3 data accuracy ratios



It was also observed that unlike in prior tests, ECHO performed better than Bluetooth. Specifically, DA for BH3-3 over ECHO was 5.4% while DA for BH3-5 over Bluetooth was 5.3%. The researchers could not attribute a cause to this observation, but included it as factor for the rationale to deselect the Bluetooth protocol for follow-on phases.

c. Maximal Link Distance

The researchers’ time-synchronized GPS data with sensor data and calculated maximal link distances from rounds 2, 3 and 5. As presented in Table 13, these distances ranged from 102.5 meters to 192.7 meters. To establish a

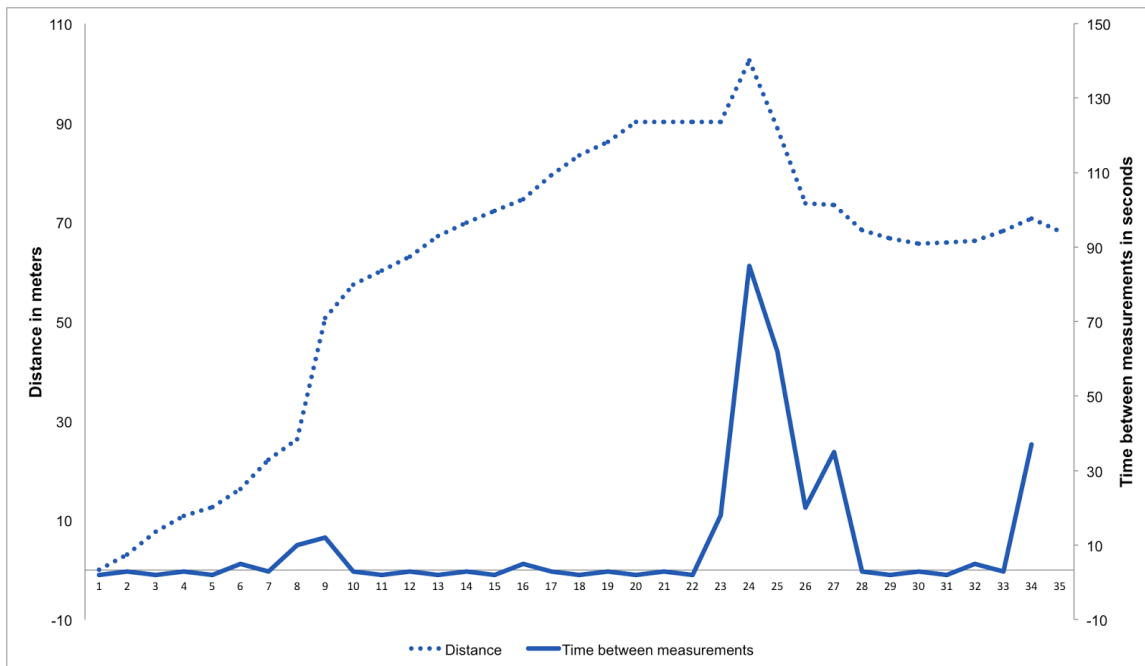
maximal link baseline, the researchers agreed to use the average of the three values, 135.5 meters. This baseline was used for follow-on phases.

Table 13. Phase 2a: maximal link distances for rounds 2, 3, and 5

Round	Maximal Distance	Best Equivalent Throughput	Worst Equivalent Throughput
2	102.5 meters	50%	1.2%
3	111.2 meters	50%	0.4%
5	192.7 meters	50%	0.3%

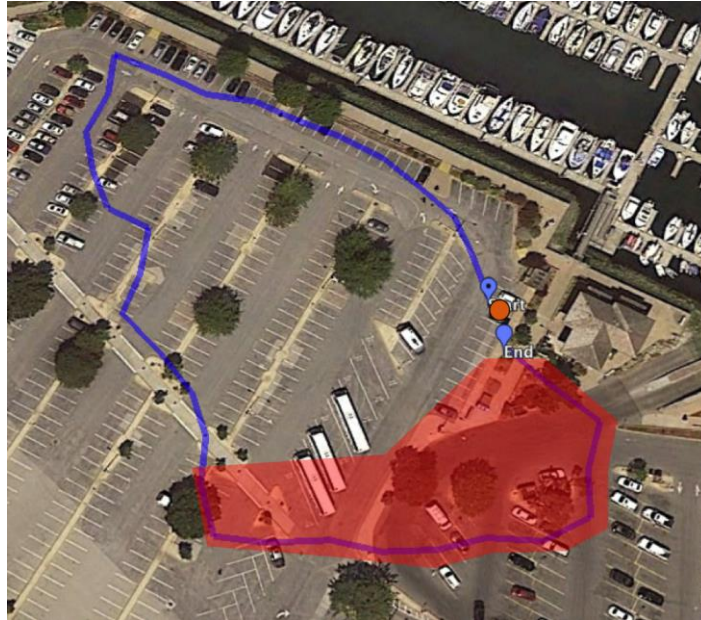
In line with literature review, the researchers observed a decrease in throughput as the distance between the sensor and the acquiring node increased (Figure 77).

Figure 77. Phase 2a: impact of distance from acquiring node on data receipt interval duration



Additionally, the researchers observed a “dead zone” presented in Figure 78. This zone was located South to South-West of the central node.

Figure 78. Phase 2a: potential LOS dead zone that impacted throughput



Despite the closer proximity, the observed data throughput in this zone was less than 9.6%. It is submitted that LOS issues contended with throughput while Researcher 1 was traversing this area.

2. Phase 2b: SIM-G and SKYi Test

The primary objective of Phase 2b was to test for maximal link distance between the SKYi and the SIM-G sensor. Consequently, throughput and reachback data were not directly collected. However, the analysis of the data from the Triax Cloud showed that 108 and 83 impacts respectively registered during rounds 1 and 2 of this phase, indicating reachback was achieved during the timeframe of this phase.

a. Maximal Link Distance

During Phase 2b, Researcher 1 was equipped with the SIM-G 2922 sensor and conducted impact testing along a predesignated Northeast path. Researcher 2 assumed the role as the C2 control and monitored the SKYi sensor receiver from a central point. The objective was to evaluate the maximal distance that could be traveled before the SKYi registered that the sensor was no longer active (Figure 79).

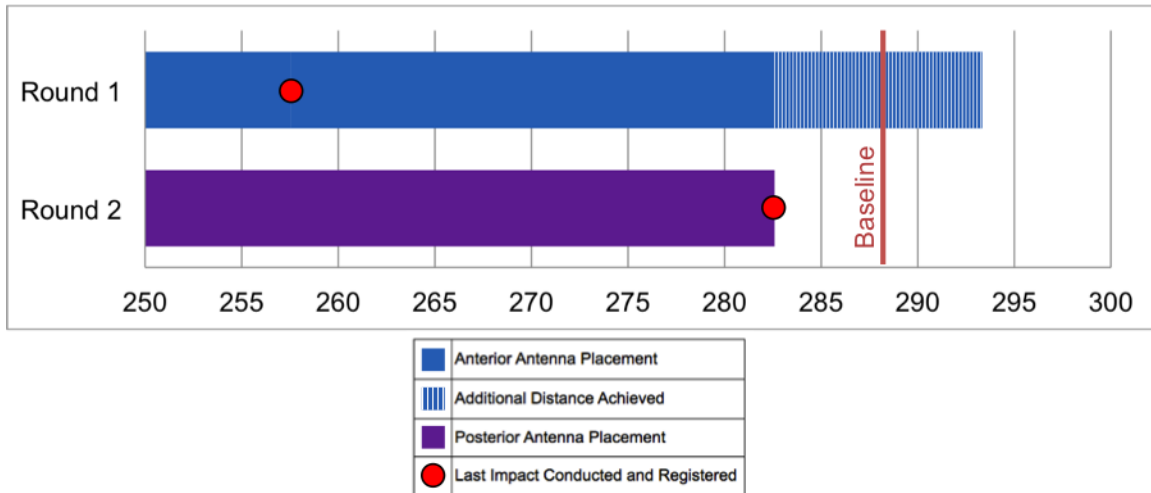
Figure 79. Phase 2b: SKYi display indicating that an active SIM-G sensor has lost connection



The researchers tracked the path using a GPS to calculate the maximal distance reached once the SKYi indicated that connection was lost. Two rounds of tests were conducted to test for anterior and posterior antenna placement. The former test was conducted in accordance with vendor suggested best use guidance. Specifically, a further maximal reach was achieved by directing the antenna side (back) of the SKYi toward the sensor.

Data showed that the SKYi had a 9.7% further maximal link distance with an anterior antenna placement than when used with a posterior orientation. Further analysis showed that the last recorded impact for round 1 was 257.5 meters from the central node. Impact tests were not conducted closer to the maximal link boundary during this round. However, based on the data from round 2, along with vendor performance statements, the researchers concluded that their tested measured maximum link reach was accurate as depicted in Figure 80.

Figure 80. Phase 2b: SKYi maximal link distance with baseline



An average of the two values, 288 meters, was used as a maximal link distance baseline for follow-on phases.

3. Findings Summary

During Phase 2, the researchers established benchmarks for BH3 data throughput, data utility, and data accuracy. Additionally, maximum link distance baselines for BH3 over ECHO and SIM-G were established. Table 14 reflects new values for benchmarks as well as baselines from Phase 1.

Table 14. Phase 2: findings summary: baselines and benchmarks

			Phase 1	Phase 2
Factor	Sensor	Protocol	Baseline	Benchmark
Data Throughput	BH3	ECHO BT	39.5%	19.6%
			90.1%	Not established
	SIM-G		85.0%	Not established
	SIM-P		90.0%	
Data Utility	BH3	ECHO BT	22.4%	4.7%
			45.9%	Not established
	SIM-G		85.0%	Not established
	SIM-P		90.0%	
Data Accuracy	BH3	ECHO BT	18.3%	2.6%
			44.3%	Not established
	SIM-G		85.0%	Not established
	SIM-P		90.0%	
Maximal Link Distance	BH3	ECHO BT	135.5 m	Not established
			Not established	Not established
	SIM-G		288 m	Not established
	SIM-P		n/a : data stored on iPhone	
Reachback	BH3	ECHO BT	No reachback capability	
			SIM-G	89.0%
	SIM-P	No reachback capability		

As previously stated, the researchers did not establish benchmarks for BH3 over Bluetooth due to BH3’s intermittent connectivity within 6.5 meters from the control node. Furthermore, iPhone Triax application captures SIM-P impacts. It was presumed that an iPhone would be on a person, in close proximity to a sensor. Hence, the maximal link distance was not established during this phase or follow-on phases.

C. PHASE 3: MULTIPLE SENSORS TESTING

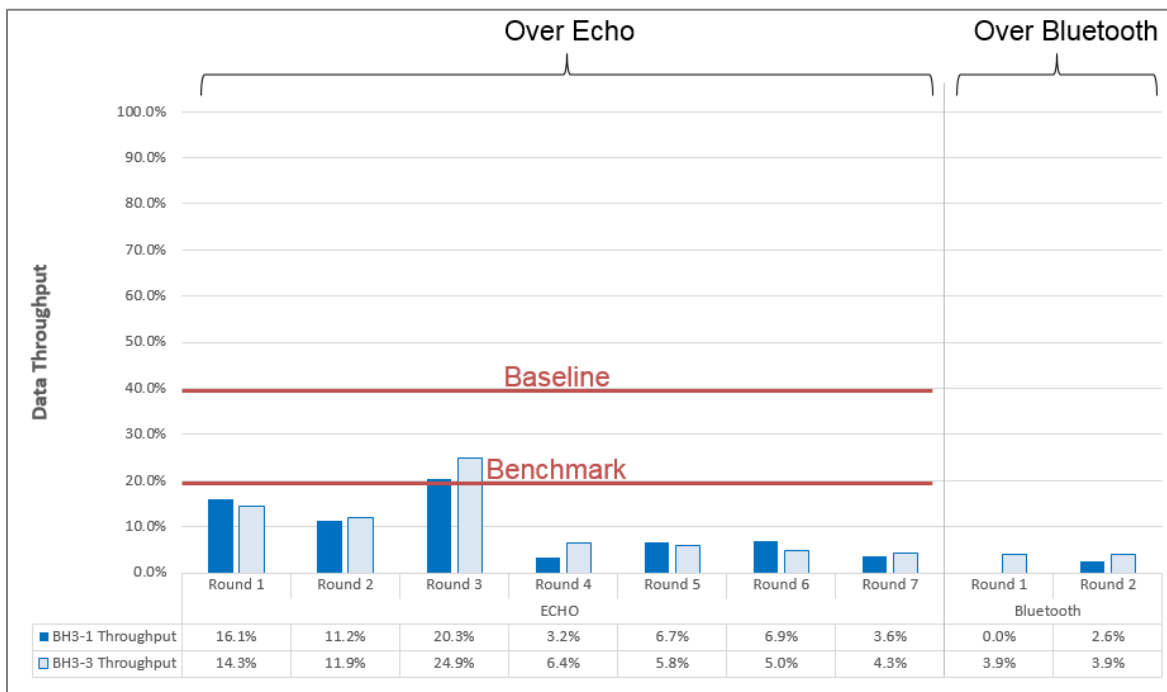
During this phase, the researchers conducted comparative analysis on data collected on the BH3 sensors versus data collected in the OmniSense application. Additionally, to determine benchmarks for Triax sensors, the

researchers performed comparative analysis on the control impacts conducted on the SIM-P versus simultaneous impacts conducted on the SIM-G. Ultimately, the results of the data derived from this phase served as an expected benchmark for testing in a simulated tactical environment.

1. Throughput: BioHarness 3

In this phase, the researchers calculated data throughput for BH3, SIM-G, and SIM-P sensors and compared these values to previously determined baseline and benchmarks. This phase was conducted in nine rounds. Each round had slight modifications to setup configurations, mostly changing the placement of the SKYi receiver to determine the SKYi reachback capabilities. Additionally, the researchers changed the placement of the OmniSense receiver. This placement change is evident in the BH3 data throughput (Figure 81).

Figure 81. Phase 3: data throughput

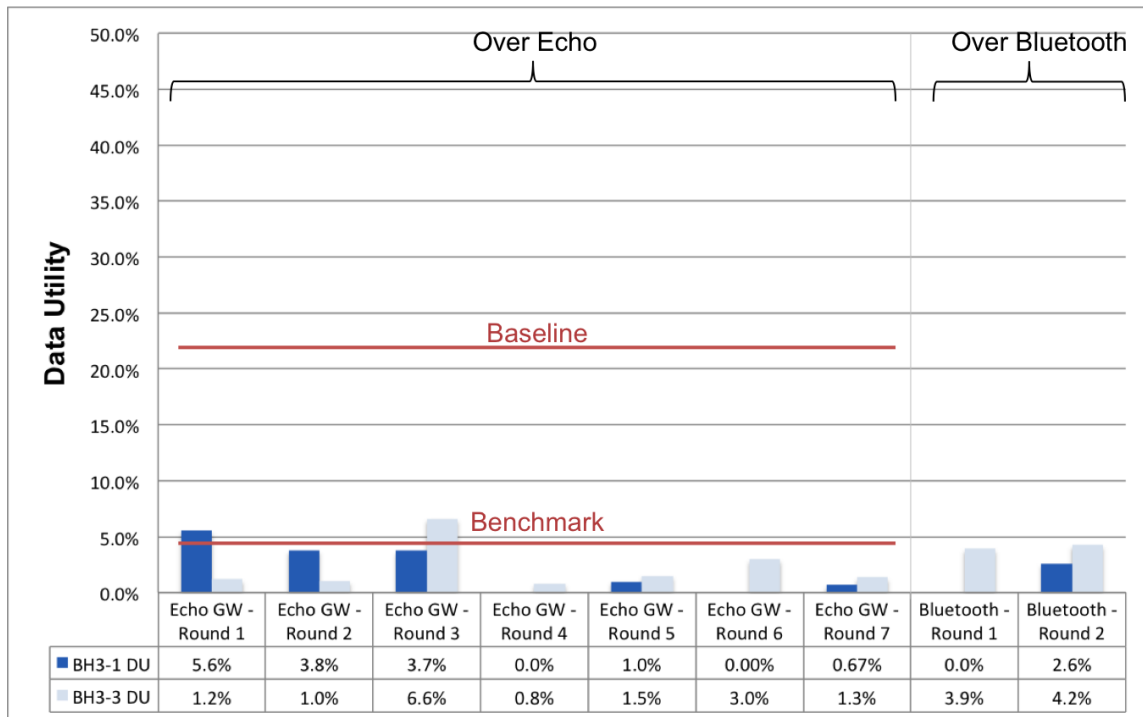


In rounds 1–2, the OmniSense receiver was on the ground. In round 3, the researchers moved the receiver up at 2.4 meters above the ground. Elevating the receiver contributed to an average of 40% increase in data throughput for BH3 sensors. The researchers also noted that the round with a higher receiver placement was the only round that exceeded the predetermined data throughput benchmark of 19.6%. Both sensors performed fairly equal, regardless of the positioning on Researcher 2; BH3-1 was worn per specifications; BH3-5 was placed near the right clavicle.

2. Data Utility and Data Accuracy

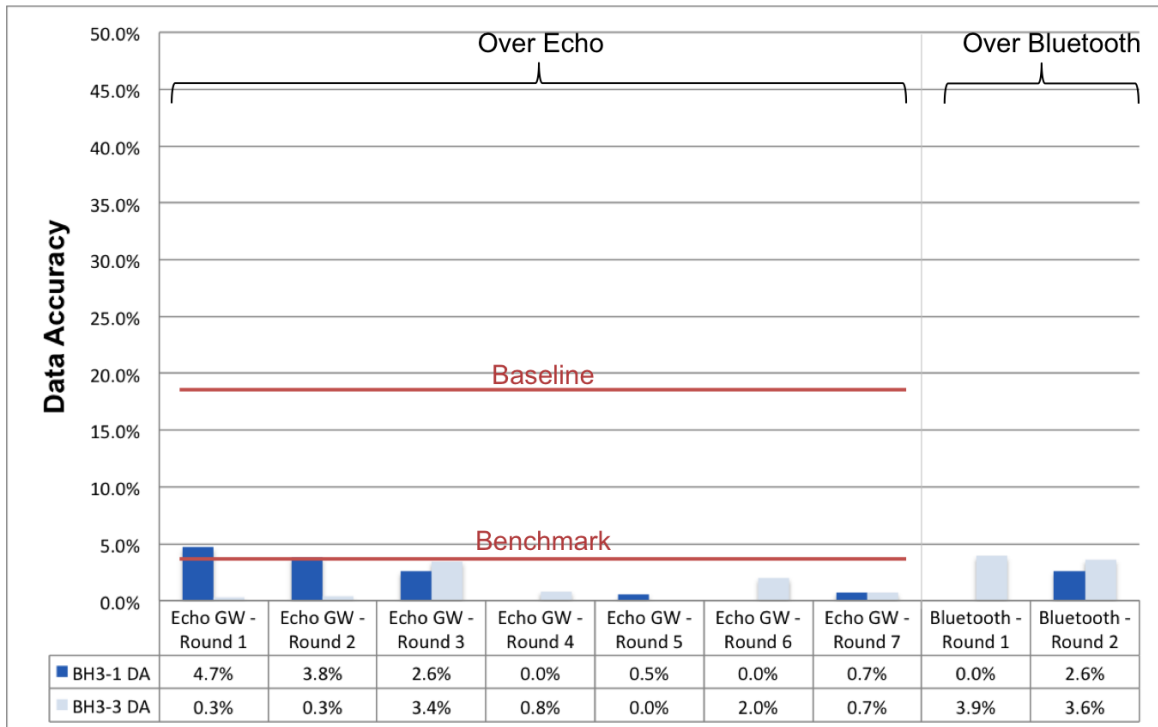
Figures 82 and 83 represent data utility and data accuracy ratios, respectively. The researchers observed that DU and DA performed, on average, below the established benchmark. The researchers speculate that the introduction of the SIM-G and SIM-P into the testing environment may have played a role as these add to signal pollution on the 2.4 GHz spectrum.

Figure 82. Phase 3: data utility ratios



When looking at individual rounds for DU, the researchers observed that the BH3-1 sensor performed 19% better in round 1 than the benchmark of 4.7% established during Phase 2. Similarly, in round 3, the BH3-3 sensor performed 40% better than the benchmark. However, their respective ratios fell within the DU ranges observed in Phase 2b during benchmarking and therefore were not considered as outliers.

Figure 83. Phase 3: data accuracy ratios



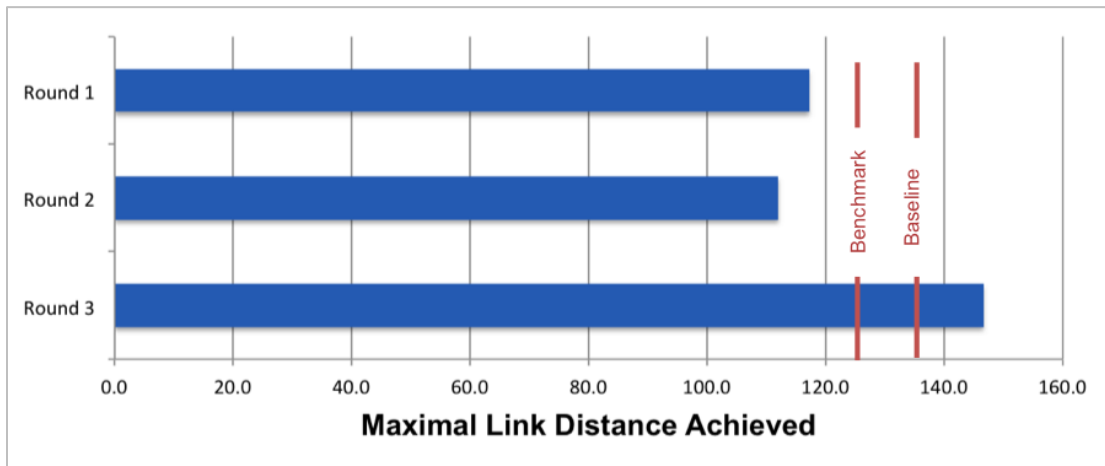
In conducting a review of the calculated DA ratios, the researchers found similar trends as observed with DU. Additionally, it was observed that while the placement of the ECHO antenna at 2.4 meters above ground level during round 3 significantly improved the throughput rate, it did not have a marred impact on either data utility or data accuracy.

3. Maximal Link Distance: BioHarness 3

The researchers observed that the maximal link distance for the BH3 sensor ranged from 6.3 meters over Bluetooth to 146.6 meters over ECHO. Additionally, it was noted that the elevated antenna placement during the third round of testing improved maximal link distance by 8.2% over the previously established baseline.

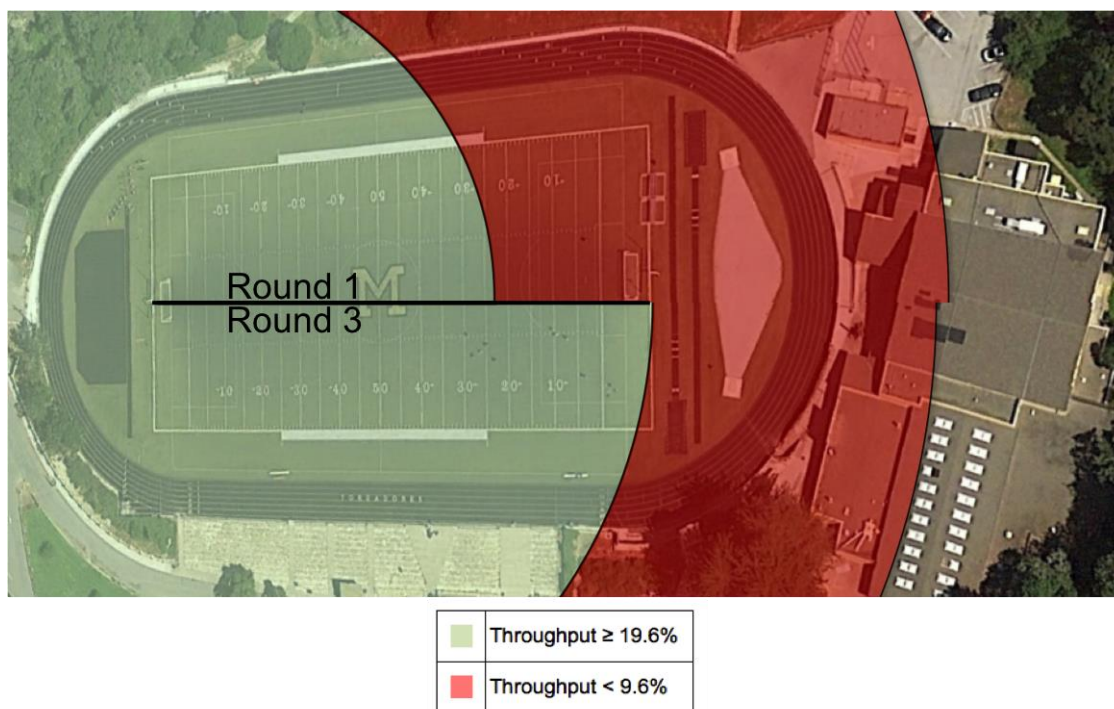
Based on the rounds 1–3 data (Figure 84), the researchers calculated an average maximal distance. The average of 125 meters was then established as the benchmark for the field experiment.

Figure 84. Phase 3: BH3 maximal link distance



The researchers mapped the BH3 throughput for the testing area as presented in Figure 85. They observed a 33% gain in distance by placing the ECHO receiver 2.4 meters above ground level.

Figure 85. Phase 3: distance gain by placing receiver 2.4 meters above ground level



4. Maximal Link Distance: SKYi and SIM-G

During this phase, the researchers focused on maximal link distance for the SIM-G system during rounds 4–7. Specifically, they tested to ascertain whether adding the BH3 to the testing environment would impact the maximal link distance.

Using a similar approach as in Phase 2 for testing the maximal distance, Researcher 1 monitored the active link status on the SKYi as Researcher 2 traversed the preset path. In addition to testing for distance, the researchers also tested for posterior and anterior antenna orientation as well as for the effects of placement elevation. Finally, during rounds 6–7, the researchers tested the Triax Cloud reachback by conducting a sensor impact once at the maximal distance point.

In reviewing the data, the researchers found that antenna orientation affected maximal distance from 5.8% at ground level to 10.8% at one meter

above ground level. Additionally, it was observed that the placement elevation impacted maximal distance by 23.8% (Table 15).

Table 15. Phase 3: SKYi and SIM-G maximal link distance

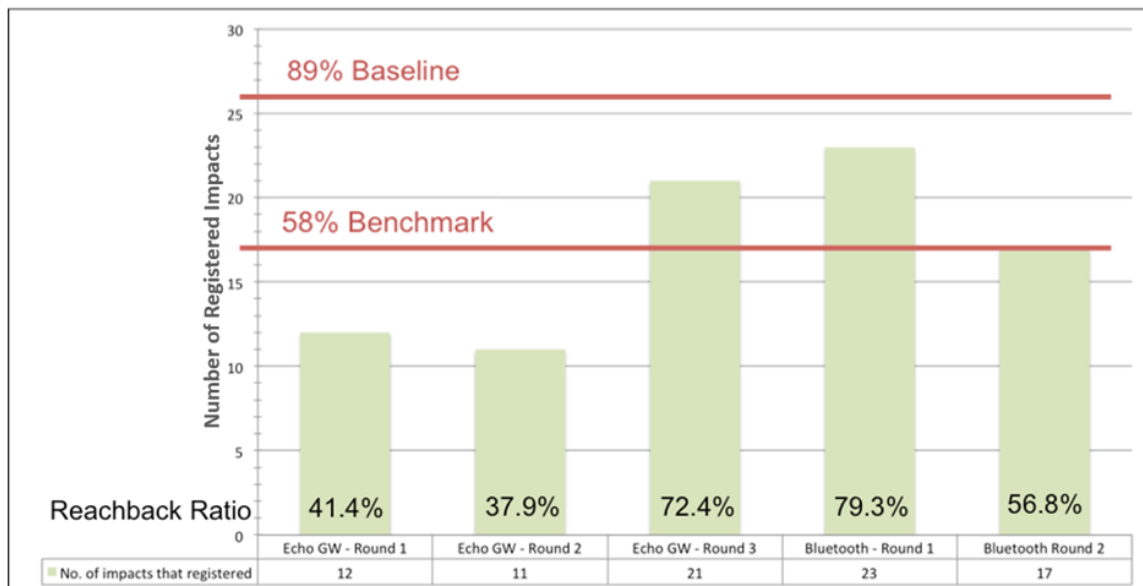
Phase 3 Round No.	Antenna Orientation	Receiver Placement	Maximal Link Distance	Final Impact Registered
4	Anterior	Ground level	145.8 m	N/A
5	Anterior	1 m AGL	180.5 m ¹	N/A
6	Posterior	Ground level	137.8 m	Y
7	Posterior	1 m AGL	162.9 m	Y

¹Researcher 2 reached Southern wall of gymnasium and could not travel any further

5. Reachback: Triax Cloud

The objective for reachback in Phase 3 was to establish a benchmark for follow-on experimentation in the field experiment. Researcher 2 conducted impact testing at ten-yard intervals (9.144 m) as well as at four additional locations on a football field in both directions. There were a total of 29 impacts per test round. This test was repeated over five rounds with reachback ratios ranging from 37.9% to 79.3% (Figure 86).

Figure 86. Phase 3: reachback benchmarking for SIM-G and SKYi



The researchers calculated an average reachback ratio of 58%, which then was implemented as the benchmark.

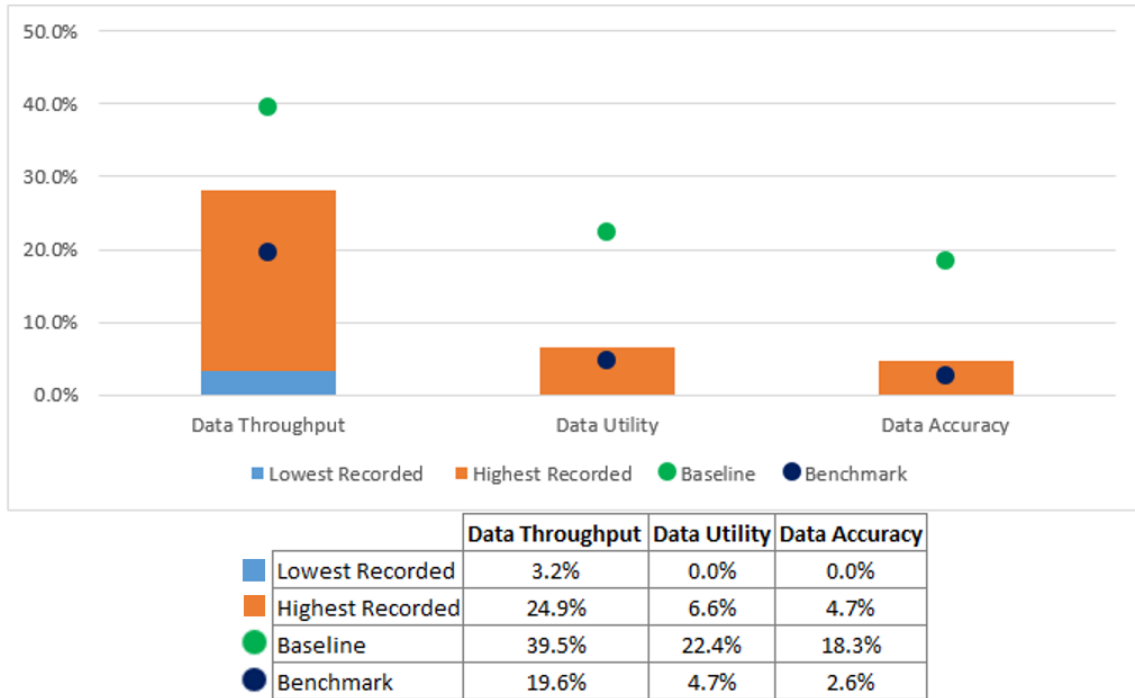
6. Findings

Table 16 provides the baselines and benchmarks established during Phases 1 through 3. After Phase 3, the researchers observed that BH3 sensors in an uncontrolled environment are capable of meeting and exceeding the pre-established benchmarks (Figure 87). The highest throughput values were attributed to the receiver placement at a higher position, 2.4 meters up from the ground.

Table 16. Phase 3: findings summary: baselines and benchmarks

Factor	Sensor	Protocol	Baseline	Benchmark
Data Throughput	BH3	ECHO	39.5%	19.6%
Data Utility			22.4%	4.7%
Data Accuracy			18.3%	2.6%
Maximal Link Distance	BH3	ECHO	135.5 m	125 m
	SIM-G		288 m	180.5+ m
Reachback	SIM-G		89.0%	58.0%

Figure 87. Phase 3: BH3 throughput, data utility, and data accuracy summary



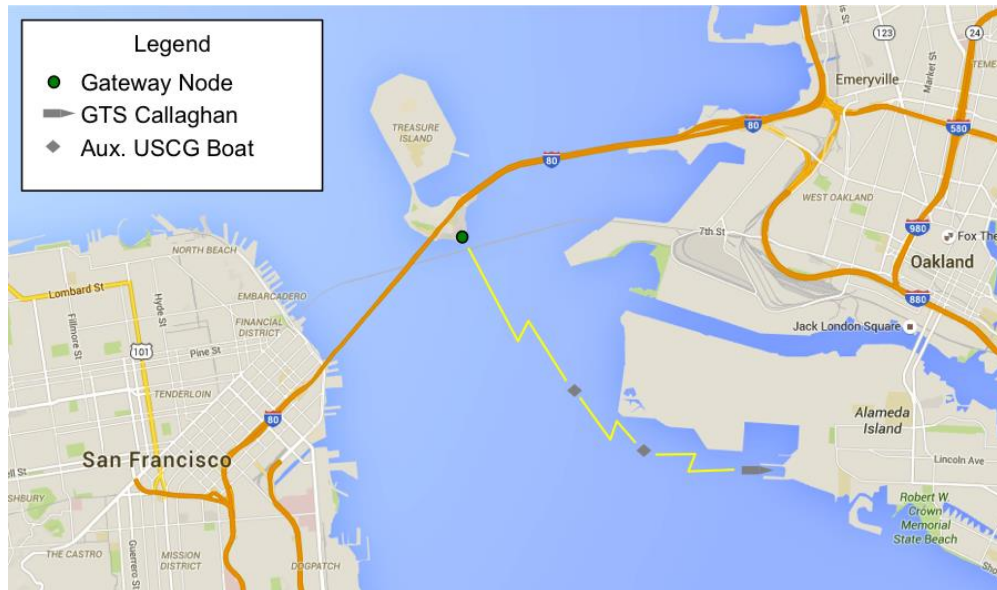
The researchers used Phase 3 data to establish SIM-G benchmarks for maximal link distance and reachback. It was observed that the gymnasium’s structural interference impacted the maximal link distance when compared to the previously established baseline. Specifically, structural interference attributed to a 34.5% reduction in maximal link distance. This was observed in the achieved maximal link distance of 180.5 meters during this phase of testing. The benchmarks, as reflected in Table 16, were used to evaluate sensors’ performance during the field experiment.

D. FIELD EXPERIMENT: VBSS ABOARD GTS ADM W.M. CALLAGHAN

The main purpose of this field experiment was to test the data reachback capabilities within constraints of a simulated maritime tactical environment. As described in Chapter III, the researchers utilized the CENETIX TNT testbed for this experiment. Specifically, the researchers employed MANET concepts in an

attempt to connect sensor receiver nodes via WaveRelay radios to a gateway node. The researchers leveraged two Auxiliary Coast Guard boats with MPU4 WaveRelay radios to overcome the communication gaps between the ship and the gateway antenna on Yerba Buena Island (YBI) (Figure 88).

Figure 88. Phase 4: field experiment network reachback to gateway via auxiliary U.S. Coast Guard boats



Both researchers were outfitted with BH3 sensors. Researchers wore one BH3 sensor per specification and placed the second BH3 sensor in their uniform's right breast pocket. In addition, each researcher carried one SIM-G and one SIM-P sensor and conducted impacts at various locations throughout the ship.

Phase 4 consisted of two rounds. During each round, the researchers alternated traversing the ship following the ISI pattern. While one researcher traversed the ship, the other researcher remained on the bridge, in close proximity to the ECHO receiver.

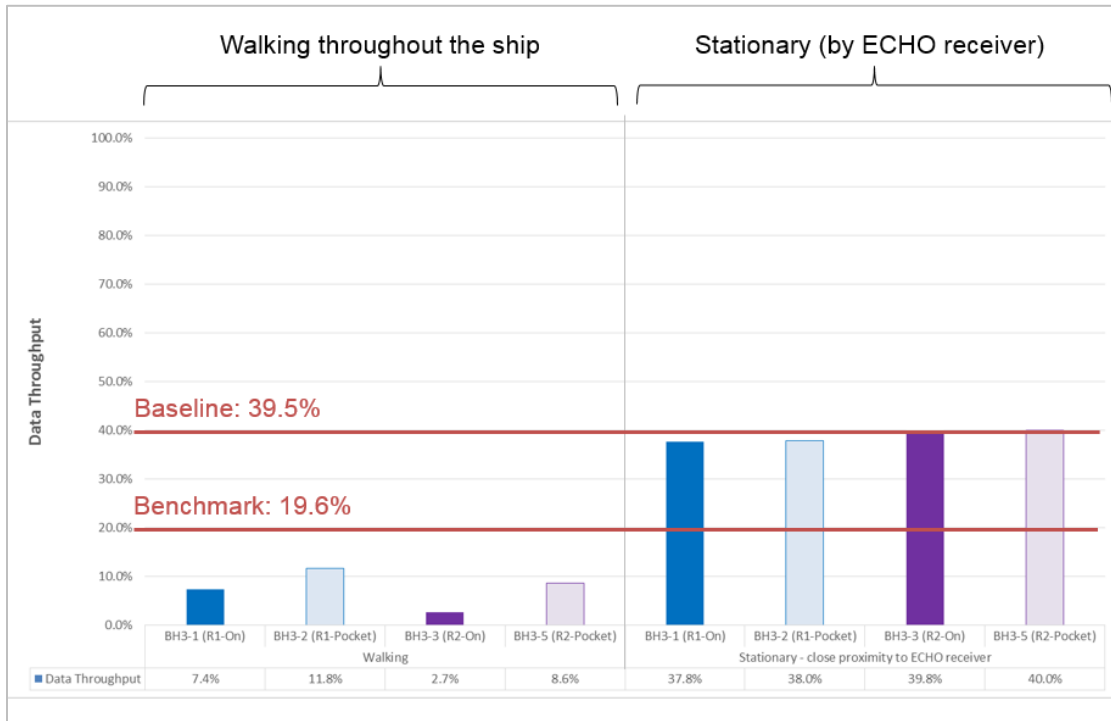
1. Throughput

Based on findings from Phases 1 through 3, the researchers agreed that the field experiment would not include testing BH3 over Bluetooth. Therefore, all analyses hereinafter for BH3 includes data collected over ECHO.

a. BioHarness 3

Upon completion of this phase, the researchers observed that BH3 sensor transmission rates met both, the benchmark and the baseline (Figure 89). However, this was true only when the researchers were either on a bridge within close proximity of the ECHO receiver or on the main deck facing the ECHO receiver (Figure 90). The lowest data throughput was observed during time periods when the researchers were traversing the ship. Researcher 2 spent longer time (total of 33 minutes) walking through the ship than Researcher 1 (total of 20 minutes). Additionally, Researcher 2 went further down below deck than the Researcher 1. This is reflected in data throughput. Data throughput for Researcher 2, on average, was lower by 40.8%. This finding is in line with literature review where authors attributed vessel structure to low data transmission.

Figure 89. Phase 4: BH3 data throughput

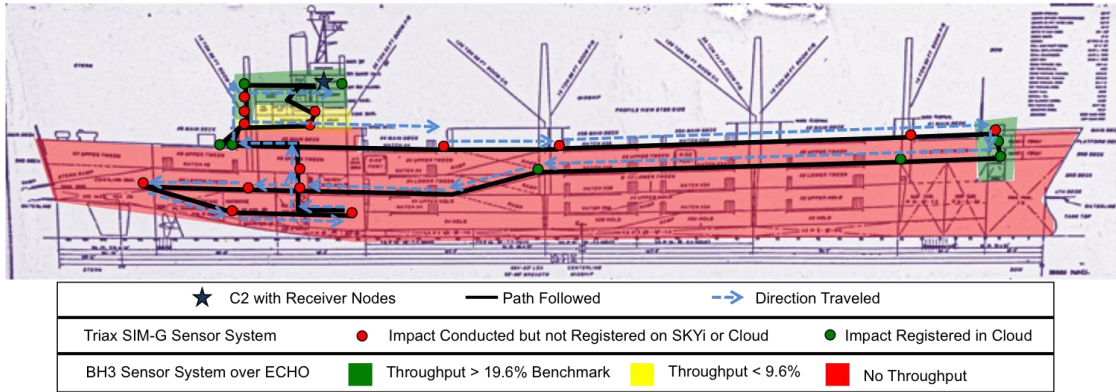


During this phase, the researchers also noted that while traversing the ship the data throughput was higher for the BH3 sensor that was placed in a pocket than the BH3 that was worn per specifications by an average of 5% between both rounds. The BH3 sensors that remained within close proximity to the ECHO receiver achieved data throughput that exceeded the benchmark and met the baseline.

b. SIM-G and SIM-P

During this experiment, the researchers conducted 41 impacts to SIM-G and SIM-P sensors while traversing the ship. The data show that only 30 impacts (73.1%) were registered on the SKYi and 14 impacts (34.1%) were registered in the Triax Cloud. Figure 90 visually depicts the impacts conducted during this experiment. The 34.1% reachback was below the pre-established baseline of 89% and benchmark of 58%.

Figure 90. Phase 4: data throughput and SKYi reachback



2. Data Utility and Data Accuracy

The researchers observed that DA and DU benchmarks were met while the researchers acted as C2 in the pilot house (Figures 91 and 92).

Figure 91. Phase 4: data utility ratios

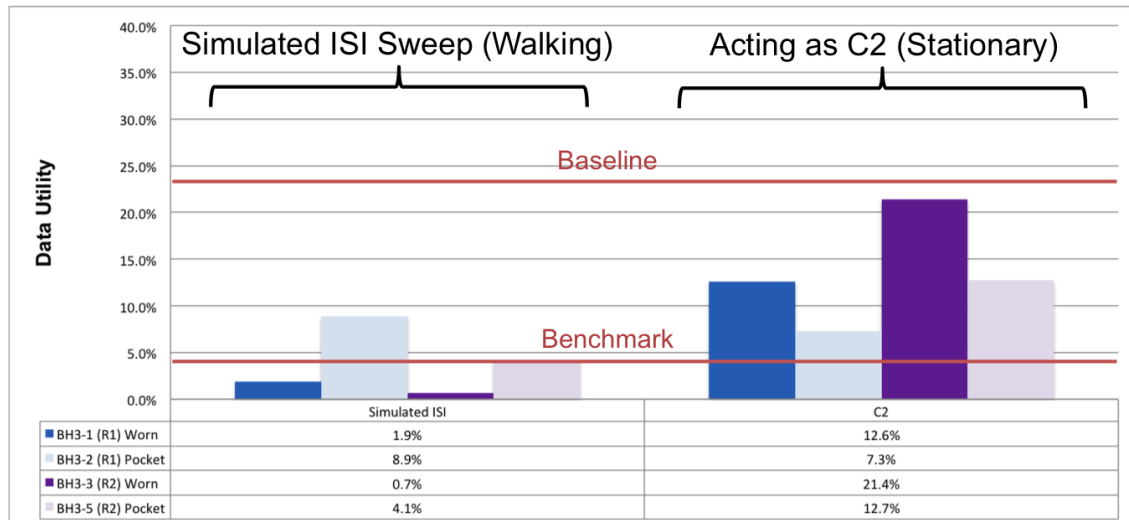
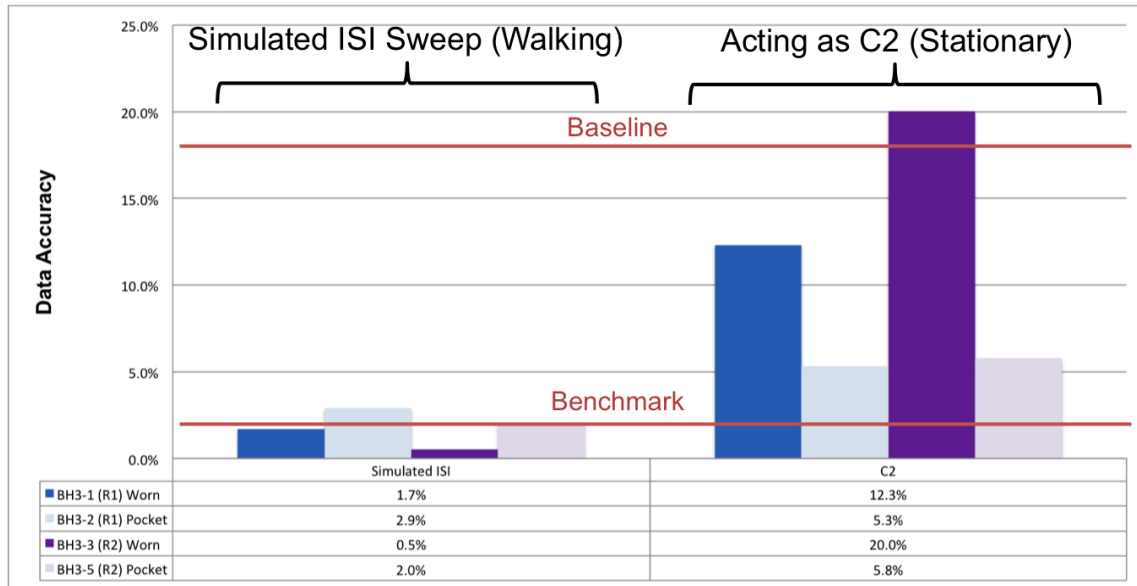


Figure 92. Phase 4: data accuracy ratios



This observation was as expected due to the proximity to the ECHO gateway. On average, the calculated DU and DA ratios were on par with the benchmarks set

3. Reachback: MANET Challenges

During the first 15 minutes while setting up for the experiment, the researchers observed an approximate 30-second link connectivity between the ship and the CENETIX gateway on the YBI. This was the only account for a successful connection during a four-hour period. This connectivity issue was attributed to environmental conditions. During the field experiment, there were 40-knot winds with six to nine feet swells. The auxiliary boats providing relay support had to abort the experiment for safety reasons. Although the Yagi antenna showed favorable results during the pre-experiment test in Monterey Bay area, it was not able to reach the CENETIX gateway from the ship to the YBI. Consequently, during round 2 of this phase, the researchers resorted to another means of reachback by using an Android phone as a hotspot. The Android phone utilized a 4G connection. Once the researchers connected to the hot spot, the SKYi started data transmission to the Triax Cloud.

The connectivity loss due to environmental constraints was in line with other theses (Chapter II) that conducted experiments utilizing the CENETIX TNT testbed. As in other experiments, the researchers briefly observed that the positioning of the auxiliary boats played an important role in establishing the connection. It was noted that proper relay node positioning required continual contact with the auxiliary boats.

The researchers found that MANET utilizing WaveRelay radios is a feasible solution for establishing a connection and transmitting the data. In addition, the researchers observed that additional manpower was required to maintain a continual communication with the auxiliary boats and the CENETIX network operation center back at NPS.

4. Findings

Table 17 outlines the findings of the field experiments. The researchers observed BH3 data throughput, data utility, and data accuracy that met benchmark. However, benchmark was met only when sensors were within close proximity of the ECHO receiver. The maximal link distance for SKYi was 132 meters within LOS (from the bridge to the bow of the ship). The reachback of the SKYi was only 34.1% falling below the pre-established benchmark and baseline.

Table 17. Phase 4: findings summary post field experiments

Factor	Sensor	Protocol	Baseline	Benchmark	Field Experiment	
					Below Deck	By ECHO
Data Throughput	BH3	ECHO	39.5%	19.6%	2.7%	38.9%
Data Utility			22.4%	4.7%	0.7%	21.4%
Data Accuracy			18.3%	2.6%	0.5%	20.0%
Maximal Link Distance	SIM-G		288 m	180.5+ m	132 m within LOS	
Reachback	SIM-G		89.0%	58.0%	34.1%	

V. CONCLUSIONS AND FUTURE RESEARCH

A. CONCLUSIONS AND RECOMMENDATIONS

The authors concluded that the system of sensors used for experimentation has the ability to fill some of the historical health information gaps that currently prevail in Defense Health. Specifically, as restated in Table 18, these sensors only track four of the seven desired health measurements for tactical and population health needs.

Table 18. Summary of desired and sensor captured health measurements

	BH3 Sensor	<u>Triax</u> Sensor
Heart Rate	•	
Breathing Rate	•	
Core Temperature		
Glasgow Coma Scale	•	•
Blood Pressure		
Concussive Forces		•
Air Quality		

Based on the experimentation conducted in this research, the authors determined that the tested devices are not efficacious for a MIO tactical environment. It was found that while these sensors met the requirement for wireless communication, the constraints inherent to a shipboard environment significantly impacted expected throughput performance benchmarks. Specifically, near real-time health information gaps prevailed in excess of 15

minutes, which is outside of best practice guidelines for vital sign measurement frequency.

The authors submit that if the sensors were reconfigured to synchronize with a mobile smart device that communicates via a MANET, these sensors could meet the needs of MIO tactical personnel. This is contingent on having an application suite that is capable of collecting data from multiple biomedical sensors regardless of sensor vendor.

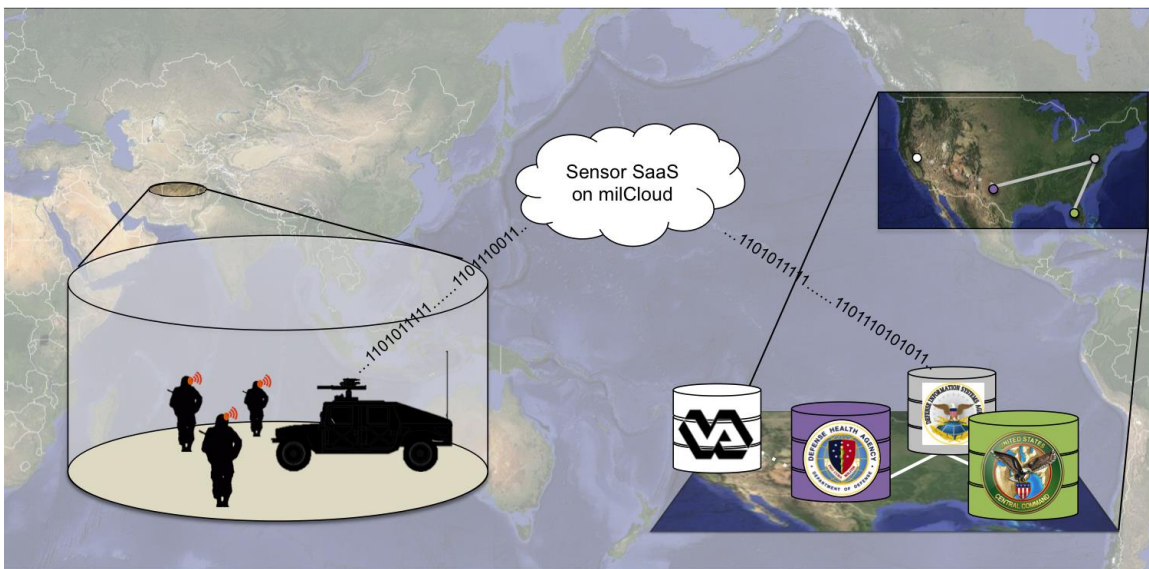
In their evaluation of the tested biomedical sensors (Table 19), the authors found that the sensors largely met or exceeded threshold criteria (met or exceed the established benchmarks and or baselines). It was found that the BH3 sensor was subjectively uncomfortable to wear as it slightly exceeded the obtrusiveness factor in thickness. However, it did perform beyond expectations in its ability to store data for post hoc retrieval, which offers an opportunity for manual data sharing and potential Electronic Health Record integration. The Triax SIM-G sensor, on the other hand, offered a small form factor but failed to register offline impacts as benchmarked once in record mode.

Table 19. Conclusions: summary of sensor performance

Dimension	Factor	Criterion	Grading		
			Under 85% from benchmark	Benchmark ± 15%	Baseline or better
Technical Performance	Effectiveness	Transmission Distance in meters		BH3	SIM-G
		Connectivity		BH3 / SIM-G / SIM-P	
	Readiness	Ease of deploying sensors in a maritime environment		BH3 / SIM-G / SIM-P	
	Implementability	Form Factor Weight in grams <ul style="list-style-type: none"> • Sensor only • Sensor & Straps Thickness in mm	BH3	SIM-G	SIM-P
		User Friendliness (subjective measurements on sliding scale)		BH3 / SIM-G / SIM-P	
	Reliability	Battery (in hours of operating time between charging)		BH3	SIM-G / SIM-P
		Data Storage		SIM-G	BH3 / SIM-P
Information Quality	Data Relevance	Data Richness Variety of data	SIM-G / SIM-P	BH3	BH3 (with GPS module; not available for testing)
System Quality	Data Accuracy	Data Utility (data accuracy in health status measurements only) Data Accuracy (all measurement sets from the originator)		BH3 / SIM-G / SIM-P	

The authors were favorably disposed of the reachback capabilities offered through the SIM-G and the Triax Cloud. The integration of the Triax Cloud data visualization platform stood out as meeting health information reachback capabilities desired of any biomedical sensor system. However, this capability is currently limiting in that the sensor data can only be sent to the vendor Cloud for data visualization and sharing. It is submitted that if this capability were refined for integration into Software-as-a-Service capability on milCloud, it has the potential to meet the needs of leadership at the tactical, operational, and strategic layers (Figure 93).

Figure 93. Future concept of biosensor data integrated into the milCloud



B. FUTURE RESEARCH

The authors concluded that this system of sensors did not entirely meet the requirements for a MIO environment due to the constraining signal propagation factors. This conclusion does not negate the value of such or similar sensor systems. The authors submit, that there are several opportunities for future research that could leverage the findings of this work. The following are potential research vectors for consideration:

- Developing a universal biosignal mobile smart device application. Such an application should have the ability to acquire biosignals from multiple disparate COTS sensors and transmit these via DOD fielded MANET technologies to a simulated health data server.
- Testing the efficacy and viability of the sensors used in this experiment in a ground environment, similar to the conceptual future state presented in Figure 89.
- Identifying a best practice for the receipt of health data frequency from biomedical sensors in a tactical environment. Such a study should address both medical necessity of vital sign measurement frequency as well as the information demands of tactical commanders.

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APPENDIX A. DEFINITIONS

(1) Biomedical Sensors

“In medicine and biotechnology, sensors are tools that detect specific biological, chemical, or physical processes and then transmit or report this data. Some sensors work outside the body while others are designed to be implanted within the body” (National Institute of Health, n.d.).

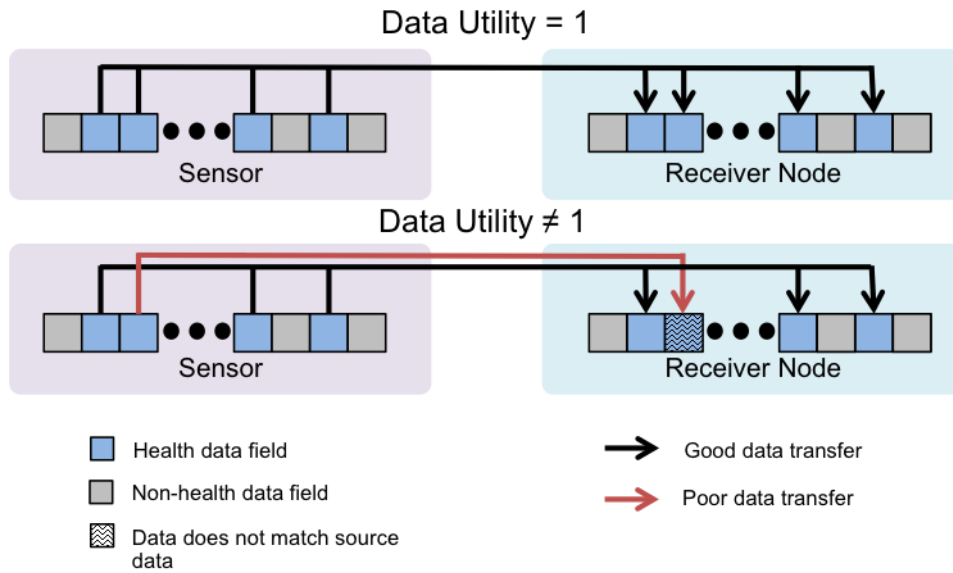
(2) Data Throughput

Data throughput is the ratio of acquiring node received measurement recordings (data sets) to the number of actual measurements recordings transmitted from the sensor. This metric does not differentiate between partial or fully matched data pairs from the sensor and acquiring node.

(3) Data Utility

The data utility metric is an assessment of fully matched record pairs from the sensor and acquiring node. Of specific interest, as it applies to this research, are only medically relevant data. This concept of data utility is graphically presented in Figure 94. Visualized in the top half of Figure 94 is a fully matched record pair that would contribute $1/n$ to metric. The bottom half of the figure depicts a partially matched record pair, which would not contribute as $1/n$ to the metric.

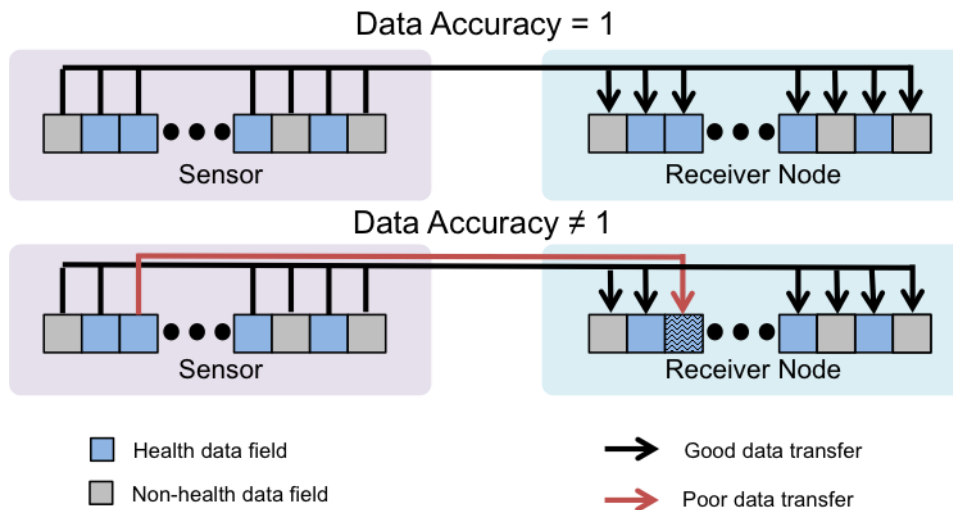
Figure 94. Data Utility graphically visualized



(4) Data Accuracy

Data accuracy: ratio of number of recordings received in the acquiring node to the number of measurements recorded on the sensor with exact data matches. This metric is an assessment of fully matched record, in both the sensor and acquiring node. Figure 95 graphically presents this concept.

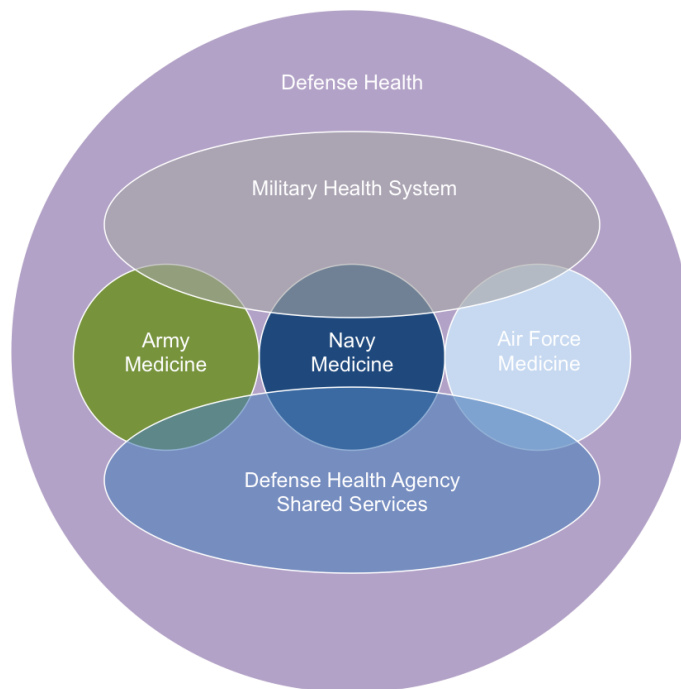
Figure 95. Data Accuracy graphical visualized



(5) Defense Health

Defense Health within the context of this document is considered all facets that have a direct relationship to the provision of healthcare to beneficiaries of the Military Health System. Such facets include the direct delivery of care, all supporting functions, such as those provisioned by the DHA's shared services, as well as any policy development. Figure 96 graphically contextualizes the scope of Defense Health.

Figure 96. Scope of Defense Health



(6) Interoperability

“The exchange and processing of data between systems via a structured format and a common vocabulary” (Stevenson, Naiman, Valenta, & Boyd, 2012, p. 1).

(7) Maritime Interdiction Operations

Worldwide operations “to enforce embargoes, intercept contrabands, prevent drug and human smuggling, and fight piracy. These operations are usually conducted by eight-man Visit, Board, Search, and Seizure (VBSS) teams, using rigid-hull inflatable boats (RHIBs) or helicopters, operating often miles from the base ship” (Nguyen & Baker, 2012, p. 1).

(8) Quadruple Aim

The Quadruple Aim is a strategic framework of care that was introduced to the Military Health System in 2009. It is composed of four elements, which support the overall value stream that the MHS provides to DOD (Figure 97).

Figure 97. Four elements of the Quadruple Aim



Adapted from: Military Health System. (2015). *Evaluation of the TRICARE program: access, cost, quality fiscal year 2015 report to congress*. Retrieved from <http://www.health.mil/Reference-Center/Presentations/2015/02/28/Evaluation-of-the-TRICARE-Program-Fiscal-Year-2015-PowerPoint-Slides>

(9) Telos Platform

The Telos platform, developed at the University of California, Berkeley (Polastre, Szewczyk, & Culler, 2005) offers several advantages over other sensor platforms, including: lower power operation; ease of use; robustness;

communication; storage; and, sensing (Polastre et al., 2005). For storage Telos has an integrated “10 KB of RAM and 48 KB of flash memory, a USB (Universal Serial Bus) interface for programming and communication, and an integrated wireless ZigBee compliant radio with on-board antenna” (Jovanov et al., 2005, p. 6). Capabilities of an ambient sensor are achieved through measures of humidity, temperature, and light sensing (Jovanov et al., 2005).

(10) The Joint Commission

The Joint Commission is an independent, not-for-profit organization that accredits and certifies more than 20,500 United States health care organizations and programs for meeting certain performance standards (The Joint Commission, n.d.).

(11) Visit, Board, Search, and Seizure (VBSS)

“Describes the maritime boarding operations developed by the U.S. military and law enforcement agencies in order to thwart piracy, smuggling, and in some cases terrorism. Other missions include custom and safety inspections requiring the capabilities of today’s navies, marines, and maritime police agencies” (Stewart, 2014, p. 3).

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APPENDIX B. EQUIPMENT USED DURING EXPERIMENTS

Table 20. Equipment used during bench and field experiments

Equipment type	Model	Additional Information
Laptop	Lenovo T400	Vendor: Lenovo OS: Windows 7 Ultimate Software: OmniSense for Windows 3.7.15 for: ~ Zephyr OmniSense Monitoring and ~ Zephyr Analysis
Laptop	MacBook Pro (Retina, 13" 2013)	Vendor: Apple OS: OS X Yosemite Ver 10.10.5 Software: ~ VMWare Fusion Pro. 7.1.3 w Windows 7 ~ OmniSense for Windows 3.7.15
Mobile	Motorola XT910	Vendor: Moto by Lenovo Android Version: 4.1.2
Mobile Computing Device	iPhone 6s 64 GB	Vendor: Apple OS: iOS 9.2 Software: ~ Triax SIM-P Ver. 1.5 ~ MotionX-GPS Ver. 24.1 Build 5049R64 ~ BLE Tool ~ BLE Scanner Ver. 1.0.7 Build 3 ~ Architecture of Radio
Mobile Computing Device	iPhone 6s 64 GB	Vendor: Apple OS: iOS 9.2.1 Software: ~ Triax SIM-P Ver. 1.5
Tablet	Google Nexus 7	Vendor: Google Android Version: 4.31 Kernel Version: 3.4.0 Software / Apps: ~ AirCasting, myFitness Companion, SenseView, SenseView Zephyr Service, Triax SIM-P Ver. 1.5
Tablet	PantechP4100	Vendor: AT&T Client Version: Red Bend vDM 4.07 Android Version: 3.2.1 Apps: AirCasting, BioInk, Zephyr Heart Monitor, Heart Rate Monitor

Equipment type	Model	Additional Information
Sensor	BioHarness 3	Vendor: Zephyr/Medtronic Software: OmniSense Live installed on laptop
ZigBee Gateway	ModFlex Mini Gateway USB	LS Research Spectrum: 2.4GHz Channel 24
Sensor	SIM-G	Vendor: Triax Software: Triax Cloud
Sensor	SIM-P	Vendor Triax Software: See iPhone 6s
Sensor Receiver	SKYi	Vendor: Triax OS: v2/201512080

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