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Antenna Design Considerations for the Advanced Extravehicular Mobility Unit

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1 Executive Summary

NASA is designing an Advanced Extravehicular Mobility Unit (AEMU) to support future manned missions beyond low-Earth orbit (LEO). A key component of the AEMU is the communications assembly that allows for the wireless transfer of voice, video, and suit telemetry. The Extravehicular Mobility Unit (EMU) currently used on the International Space Station (ISS) contains a radio system with a a single omni-directional resonantcavity antenna operating slightly above 400 MHz capable of transmitting and receiving data at a rate of about 125 kbps. Recent wireless communications architectures are calling for the inclusion of commercial wireless standards such as 802.11 that operate in higher frequency bands at much higher data rates.

The current AEMU radio design supports a 400 MHz band for low-rate mission-critical data and a high-rate band based on commercial wireless local area network (WLAN) technology to support video, communication with non-extravehicular activity (EVA) assets such as wireless sensors and robotic assistants, and a redundant path for mission-critical EVA data. This paper recommends the replacement of the existing EMU antenna with a new antenna that maintains the performance characteristics of the current antenna but with lower weight and volume footprints. NASA has funded several firms to develop such an antenna over the past few years, and the most promising designs are variations on the basic patch antenna. This antenna technology at UHF is considered by the authors to be mature and ready for infusion into NASA AEMU technology development programs.

In order to support the integration of commercial WLAN technologies on the AEMU, the use of two or three 2.4 GHz antennas is recommended to achieve reliable spherical coverage around the crew member. This recommendation is due to relatively poor RF diffusion at 2.4 GHz (this frequency is considered quasi-line-of-sight) compared to 400 MHz and is supported by a series of signal strength and 802.11 link performance measurements that are performed and documented in this work. The firms that have recently developed S-band antenna technology for use on the AEMU have also arrived at the same conclusion. The antenna prototypes produced by these firms also show a great deal of promise, but low-profile wide-coverage patch antenna technology at S-band is not as mature as it is at UHF. As a result, further research and development in this area is recommended.

As commercial WLAN technology continues to advance at its historically rapid pace, developers and standards bodies have found two ways to significantly increase network throughput and reliability; the use of multiple antennas and operation at higher frequency bands. In addition to using multiple antennas to obtain even coverage around the AEMU, these antennas may also be used to support spatial multiplexing that would provide a significant throughput boost. Transmit diversity

techniques may also be used during surface operations to increase link reliability. These techniques have yet to be exploited by the EVA community, so further exploration of this subject is recommended. New WLAN standards such as 802.11ad use frequency bands at 5 GHz and 60 GHz in addition to the 2.4 GHz band, so this paper also recommends that these frequency bands and the radio front-end hardware that drives the antennas be considered for future studies.

- Low-profile patch antenna technology, especially at S-Band and higher frequencies
- Efficient and intelligent use of multiple antennas for the proximity band, including the design of the front-end hardware
- Propagation and path loss studies at 2.4 GHz, 5 GHz, and 60 GHz around the AEMU to support the integration of more advanced commercial WLAN technologies into the AEMU and other spaceflight assets
- Packaging and mounting of antennas to the PLSS and hard upper-torso, including the routing of the antenna cables throughout the AEMU.

2 Introduction

The NASA Advanced Exploration Systems (AES) program is currently evaluating Design Reference Missions (DRMs) and technologies for manned space exploration. All of the candidate DRM target destinations are beyond LEO, so much of the existing manned spaceflight hardware must be re-designed to operate in as environment with higher levels of radiation than that of ISS. One key system currently under development is the AEMU, a replacement suit for the decades-old EMU.

A key component on the AEMU Suit is the radio, which transmits voice, telemetry, and crew health information back to the host spacecraft and subsequently a mission operations center. The current EMU radio is considerably large and heavy, and its functionality is both limited and not upgradeable. The AEMU will have to transmit and receive significantly more data than the current EMU, wirelessly interface with several different systems, and do so in a much smaller package. Clearly, a radio upgrade is needed. The AEMU radio consists of the actual baseband and RF electronics board and the antennas, the latter of which are the focus of this work.

Overviews of the EVA concept of operations, communications architecture, and AEMU radio design are given, followed by a discussion on the antenna requirements. A brief survey of recently developed AEMU antenna technologies is then provided, followed by a discussion on the use of multiple-input multiple-output (MIMO) antenna systems. This work concludes with recommendations for the AEMU antenna design and a list of open research issues. The objective of this report is to summarize and capture all of the current AEMU antenna design issues and existing antenna technologies in order to provide guidance to the technologists and program directors as they work to develop the AEMU.

3 Current EVA Communications System

As of 2014, the only operational NASA program that requires EVA is ISS, which performs routine EVAs for tasks such as payload integration and external maintenance. The EMU uses the Space-to-Space Communications System (SSCS) at its communication protocol, which supports up to five simultaneous users that include crew members and ISS. The Shuttle Orbiter was also a user on this system but is currently decommissioned. The SSCS is not an Internet Protocol (IP)-based network, but instead uses a predefined data frame structure for each of its data flows. The format of the data fields (e.g. voice, suit telemetry, and crew EKG) is also included in the SSCS specification, and these data fields are all combined into the SSCS data frame, thus they are not independently transmitted. There are three different radios that use the SSCS system: the Space-to-Space EVA Radio (SSER), Space-to-Space Station Radio (SSSR), and the Space-to-Space Orbiter Radio (SSOR). The remainder of this section focuses specifically on the SSER.

The physical layer parameters of the SSER are summarized in Table 1. The physical layer was designed to support the EVA data flows around ISS while satisfying the maximum communications range requirements of 75 m between two EMUs and 80 m between an EMU and the ISS. A tethered hardline mode is also supported while the crew member is in the airlock. The link layer of the SSCS is a five-slot time-division multiple-access (TDMA) scheme, and a new user must acquire access to the network within 30 s of acquiring an SSCS signal from another user. The TDMA burst rate is 695 kbps, so the actual data throughput rate averages out to 125 kbps, about two-thirds of which is allocated to the data fields in the 1010-bit TDMA frames. There is no high-level network protocol for the SSCS. All TDMA frames are broadcast to all users, and there are no provisions for routing data through other radios.

There are some requirements that are antenna-specific. The antenna must be low-profile so that it does not interfere with EVA mobility and poses less risk for accidental breakage. The frequency and power requirements can be inferred from Table 1. Since the crew members operate in orbit, they may orient themselves in all directions with respect to the SSSR antenna, so the antenna must provide omnidirectional spherical coverage around the EMU. The vibration requirements state that the antenna must meet all performance requirements after experiencing a 20 g emergency landing load and a +-5 g acceleration environment for

Center Frequency (Primary/Alternate Band)	414.2/417.1 MHz
Bandwidth	1.2 MHz
Modulation	2-FSK
Freq. Delta (full deviation)	486.5 kHz
Carrier Freq. Stability Requirement	+- 0.006%
Symbol Rate (TDMA Burst)	695 kbps
Error Correction Coding	Reed-Solomon and 8/9 RLL
Encoding	NRZI
Output RF Power Range	18-27 dBm
Input RF Power Range	-80.5-0 dBm

Table 1. SSER PHY Parameters

five minutes.

The actual antenna used for the existing EMU is an omni-directional resonant cavity antenna attached to the top of the SSER with Velcro. The SSER is mounted to the top of the portable life support system (PLSS) such that the actual antenna placement is behind the crew member's head. Anechoic chamber measurements of the antenna patterns indicate that there is a null located along the vector pointing from the antenna to the crew member's feet, however, this has not caused any significant performance issues during operation.

4 Communications Overview for Future EVA

The DRMs that NASA is currently considering fall into two broad mission classes with respect to EVA: spacecraft proximity operations and surface missions. Spacecraft proximity operations are EVA outside the Multi-Purpose Crew Vehicle (MPCV) and/or deep space habitat located at various destinations, including rendezvous with a small asteroid or possibly other spacecraft. The targets for surface missions are the Moon and Mars. The main differentiators between these two mission classes with respect to the radio are the size of the theater of operations and the presence of semi-permanent communications infrastructure. Spacecraft proximity operations are confined to the immediate area around the spacecraft and rely solely on the communications infrastructure available on the spacecraft itself, while surface missions may span vast areas and may include infrastructure such as relay towers and satellites.

EVA proximity operations around a spacecraft usually entail one to three suited crew members performing maintenance or installing equipment on the exterior of the spacecraft. They are expected to be able to safely operate around the entirety of the spacecraft and oriented in all directions. Even in the presence of obstructions and without line-of-sight back to the spacecraft antenna, voice and mission-critical suit telemetry are expected to be communicated at all times with minimal interruption.

In the event that crew communication is lost, the EVA will generally be aborted for the sake of crew safety until the communication problem can be resolved. In addition to the spacecraft access point and the AEMU radios, there may be other wireless assets outside of the spacecraft that require proximity wireless access, as well. These assets potentially include Robonaut(s), external payloads, wireless spacecraft health sensors, docking spacecraft, and video cameras. Instead of having separate, stovepiped communications architectures for each of these asset types, NASA is leaning towards an integrated architecture that allows for flexibility and upgradeability. This is key because large human spaceflight programs often have durations much greater than 20 years, during which time the mission objectives and wireless support requirements will most certainly change and evolve to include the support of assets and data flows never considered during the early program formulation stages.

The communications architecture for a surface mission must support longer range requirements and more users. Crew walkback range requirements for a lunar surface mission are on the order of several kilometers, which is a much greater distance than the tens of meters required for spacecraft proximity operations. A large number of wireless communications assets may also be present during the lunar or Martian mission, including relay terminals, surface experiments, robotics, satellite relays, crew habitats, and manned surface vehicles. It is expected that the AEMU will relay through a vehicle's radio or a portable communications relay when the EVA will operate far from the surface habitat.

For all mission types, the AEMU radio must support voice communications, AEMU telemetry, crew health data, video, and emergency notification messaging. In addition, the AEMU radio will need to be capable of relaying network traffic sourced by other wireless assets, including other AEMUs. One of the challenges in the design of this system is the prioritization of the various network traffic flows. For example, we do not want low-priority video traffic to degrade or interrupt voice communications between the EVA crew and mission operations personnel. Another challenge is maintaining a satisfactory level of performance for streaming network traffic that is often sensitive to network latency and jitter, both of which can be negatively affected by high-rate, bursty network traffic.

5 AEMU Radio Design Concept

The AEMU Radio Team at the NASA Glenn Research Center has developed a design concept for the AEMU radio under the AES program. The salient feature of the design is the division of network traffic onto two different radio bands; one for mission-critical data and another for all other data flows. The mission-critical band will support only voice, crew health, emergency messaging, and mission-critical suit telemetry, and this band is expected to maintain the excellent reliability record of the existing SSCS system. The second band, referred to hereinafter as the high-rate or proximity band, will carry all other data flows and will also support communication with the aforementioned non-AEMU users. The decision for a dual-band design was driven by the fact that the AEMU traffic flows fall into one of two categories; low-rate, streaming, and mission critical or potentially high-rate, non-critical, and potentially bursty. Placing both traffic types on the same network would require complex radio and network management schemes to ensure that the latter traffic would not adversely affect the former.

The key design drivers for the mission-critical band are reliable coverage throughout the theater of operations, relatively low data-rates (<200 kbps per user), and low latency and jitter. This radio network will support perhaps no more than eight simultaneous users in the most ambitious of surface exploration missions, and the user base consists of only AEMUs and their associated spacecraft and/or vehicles. Also, if this radio band is to be implemented in a software-defined platform, it would be highly desirable to configure this band with an SSCS waveform to support ISS precursor testing of the AEMU. Because of these factors, the mission-critical band is currently designed to operate between 410-420 MHz with an expected bandwidth of <5 MHz. This band is expected to work without line-of-sight between the users, and provisions will most likely be made for a secondary center frequency as a contingency against interference, similar to the SSCS. Almost all of the traffic on the mission-critical band will be UDP streams, so the link and network layers must be designed to keep network latency and jitter to a minimum. If necessary, voice traffic streamed over the wireless network can be reduced by the use of efficient audio codecs. In this case, the uncoded, high-fidelity audio can be stored locally on the suit and retrieved via hardline network after the EVA is complete for post-EVA analysis and historical record.

The high-rate band is an 802.11 wireless network operating in the 2.4 GHz Industrial, Science and Medical (ISM) band with 40 MHz of bandwidth reserved to support the potential use of a channel-bonded 802.11n configuration. This band will serve as general proximity network that is to be used by many different space assets, so it is very difficult to custom tailor this band to specific traffic types. The massive public and private investment in the development of these commercial wireless standards provides NASA with wireless solutions that should work well under most network conditions since many of these standards are designed for high-performance under a wide array of network topologies and network traffic profiles. It should be understood by the reader that this is only the current snapshot of the radio as it evolves. If modifications to the 802.11 standard are identified that facilitate its use for spacecraft proximity wireless networking, then these modifications will be considered, even if the resulting system is no longer 802.11-compliant. One such modification that would have a significant impact on the content of this

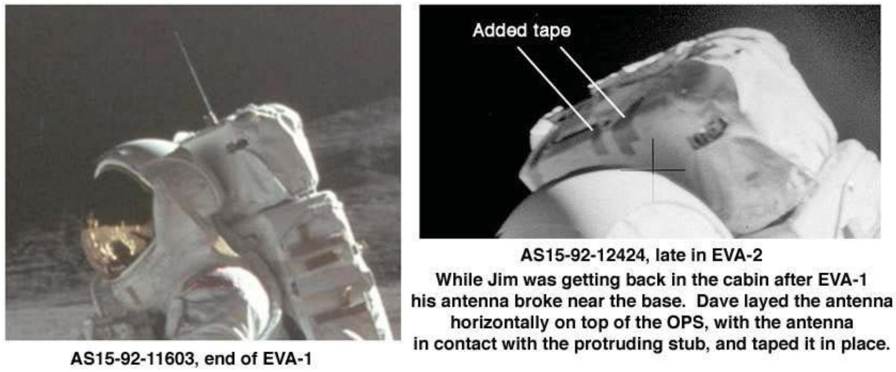

Figure 1. Before and after photos of the damaged EMU antenna from Apollo-15

report is a frequency shift from 2.4 GHz down to a lower frequency band. This not only would change the design of the antenna(s) for this band, but it also leaves open the possibility of both the mission-critical and high-rate proximity bands sharing the same antenna if the bands are close enough in frequency. Obviously, provisions would need to be made so that a malfunction in the proximity band would not affect the performance of the mission-critical band. A potential roadblock to this approach is finding an additional 40 MHz of bandwidth available around 400 MHz. This and other concepts are currently being studied, but the use of 2.4 GHz can be assumed, for now.

6 AEMU Antenna Considerations

6.1 Form Factor and Construction

The suit must allow for a wide range of motion of the crew member with minimal physical impedance or risk of damage to the suit, so it is important that low-profile antennas are used. Generally, any hardware that can be construed as an "appendage" will not be considered for the suit, which eliminates many common antenna form factors including wire dipoles and monopoles. This requirement stems from an incident during Apollo-15 when an EMU antenna was inadvertently snapped in half and had to be taped to the PLSS, shown in Figure 1. Additionally, the suitport concept may require additional consideration with regards to mounting and form factor so that the antenna does not get damaged during the suit docking process.

Before we continue, some antenna terminology will be defined. Essentially, the suit requires an antenna that is simply wearable, which implies any antenna that is small enough to be mounted on a person without considerable physical impedance. Wearable antennas can be classified as either rigid or flexible. Flexible antennas, most often constructed from conductive tapes, paints, or fibers, may be easily mounted over curved surfaces at the expense of performance and efficiency due to the distortion of the antenna element geometry. A subcategory of flexible antennas is electro-textile antennas, which are antennas constructed using conductive fibers that are actually woven into a garment. Another relevant category of antennas is conformal, which generally consist of an array of antenna elements, rigid or flexible, mounted to a flexible substrate. Conformal antennas could fit under any of the previously mentioned categories.

The most common antenna types are wire dipoles and monopoles which, as previously mentioned, are not suitable for use on the AEMU. Omni-directional cavity antennas like the one currently employed on the EMU are low-profile and should be considered as an antenna candidate, although they can be somewhat large and heavy. There are UHF antennas on the market today that possess similar RF characteristics in a lighter package, including some flexible models. Low-profile rigid patch antennas are simple to construct and widely available on the commercial market, and flexible patch antenna technology has been successfully demonstrated in various prototypes over the last 10 years. Most patch antennas are semi-directional, so more than one would need to be employed on the suit in order to achieve sufficient coverage around the suit; however, the prevalent use of microstrip patch antennas in cellular handsets has led to new designs with patterns that are more omni-directional. Conformal antennas have been successfully employed in aircraft and missile systems for many years, and conformal antennas designed specifically for a space suit have been developed in recent years. The drawback of using an array is that each element must be independently driven, which greatly increases the size and complexity of the RF front-end electronics. Aperture antennas, which include dishes and horns, are not practical for the AEMU and will not be discussed in this work.

It is important to note here that it is fairly common to incorporate multiple antenna elements within the same antenna housing, and each element may also support multiple bands. A common example of this is the use of 802.11n, which supports 2.4 GHz and 5 GHz frequency bands, as well as simultaneous operation over multiple antennas. 802.11n antennas containing four or more antenna dual-band elements are widely available and have the appearance of a single antenna with multiple antenna feeds. Newer WLAN standards and cellular standards often support 3 or more bands.

Regardless of antenna type, the antenna should be resilient to relatively mild impact and abrasion. It is likely that any antenna placed within arm's reach of the crew member will likely experience mild wear and tear as he/she moves around and works with various tools and instruments. Surface missions will most likely feature abrasive, electrically-charged dust that will coat the antenna during an EVA. If the antannas cannot easily be removed and stowed, they should also be rugged enough to endure the weight of the suit, which could be in excess of 200 lbs, during ground testing and under significant g-force during launch.

6.2 Safety/Shielding

The required transmit power of the suit radio is considerably small, on the order of 0.5 W for most design reference missions, and the crew member's head is inside a relatively spacious cavity while inside the suit, so the health concerns of having an antenna near the crew member's head are small. Still, near-field antenna testing should be performed on the suit before it can be declared safe, and the addition of shielding to protect the crew member's head may be necessary if more transmit power is needed.

Shielding can also act as a ground plane for the antenna. Most patch style antennas include the ground plane as part of the design, but there are also some antenna concepts that use a conductive layer of clothing or suit material as a ground plane. This idea may be useful for the AEMU if there is a sufficiently conductive layer in the suit garment that also contains a layer of dielectric garment material with the proper thickness between the conductive layer and the radiating element.

6.3 Polarization

Antenna polarization refers to the orientation of the electric field as waves are propagated from the antenna and may be linear or circular. If two linearly polarized antennas are not aligned, which is quite common for mobile wireless applications, there is a polarization loss component that reduces the signal-to-noise ratio (SNR) between the transceivers. Circularly polarized antennas will experience less polarization loss as the crew members change their orientation, thus circular polarization is preferred for AEMU antennas.

6.4 Frequency and Bandwidth

The mission-critical antenna will operate at UHF in the same 410-420 MHz spectrum that the SSCS operates in. The data rate requirements on this band are small (<1 Mbps), so if only a single carrier were to be used on this system, a narrowband antenna would suffice. It is expected that this band will be required to support a second carrier for use as a backup under interference conditions or if a radio becomes locked in a state with its transmitter always on. Even supporting a second carrier several MHz away from the primary carrier (the SSER uses carriers roughly 3 MHz apart), a narrowband antenna could still be used. It is important to note here that this band is likely to be software-defined, so the use of an antenna that can operate over a wide bandwidth may be beneficial, even if a small signal bandwidth is used at any given time.

The frequency range of software-defined radios is limited by the antenna and analog RF electronics, so some flexibility in these components could be greatly beneficial to the AEMU radio. To support this claim, a historical example is provided here. Before the SSCS was implemented, the Shuttle Orbiter's original EVA radio system that utilized slightly lower carrier frequencies was subject to Earth-based interference caused by radios used in the maritime shipping industry. The SSCS was designed around 410-420 MHz partly to mitigate this situation. It's possible that an unknown inference source could be found during a mission, and the option to shift the radio band away from the interference via software update rather than replacing the hardware is very attractive. In order for this capability to be realized, the spacecraft radio on this band would also have to be software-defined.

As stated in the previous section, the high-rate proximity band will use an 802.11n-based waveform operating at 2.4 GHz with support for channel bonding, so the antenna(s) used to support this interface will need to support 40 MHz of bandwidth in the 2.4 GHz ISM band. It would be ideal to have the full 98 MHz of bandwidth to support the entire ISM band, which would allow the radio to use multiple channels within the band, if necessary. It is not expected for this band to be software-defined due to the number and diversity of users that would operate on this proximity wireless band and the power draw that a high-rate software-defined radio implementation would have on a battery-powered system like the AEMU. Because of this, there is little need for excess bandwidth outside what is required by the interface standard.

6.5 RF Coverage around the AEMU

The AEMU requirements for antenna coverage and gain are slightly different for spacecraft proximity operations versus surface explorations. Omni-directional coverage is required in both cases, but proximity EVA operations will require more spherical coverage around the suit due to the multitude of orientations that the crew members experience in zero gravity. Surface operations will require more gain due to the increased distances involved, but antenna coverage along the elevation plane will be less important due to the fact that both the crew and the base station will be oriented along the same plane normal to the surface. Coverage along the elevation plane should be good enough to maintain RF links when the crew member is leaning over to pick objects up or capture them on video while on the surface.

Actual antenna gain requirements cannot be defined until a mission is defined and an end-to-end link budget is performed, so some assumptions for the average gain are made in Table 2. For proximity missions, sharp nulls in the spherical antenna pattern around the crew member can fall below the average gain, and for surface missions, nulls along the head and foot vectors can fall under the threshold, as well.

Band	Spacecraft Proximity	Surface Exploration
UHF Mission Critical Band	0	3
S-Band Proximity Comm. Band	3	7

Table 2. Assumptions for average antenna gain (in dBi) in 3D-space around the AEMU

6.6 Number and Location of Antennas

Potential locations for antenna placement include the PLSS enclosure, helmet, and the hard upper torso assembly. Antenna cabling must also be considered. Routing cables through suit joints may lead to excessive wear or breakage and is generally not accepted as a good design option. In order to reduce the number of potential failure points and keep signal loss to a minimum, care should be taken to minimize the number of coaxial connectors and adapters. Many AEMU design factors will determine the most efficient way to connect the antennas to the radio with a single cable, and these include the pressurized/unpressurized boundaries, antenna locations, the construction of the avionics enclosure, and the available conduit for routing cables inside the AEMU.

A single omni-directional UHF antenna, with a proper design and placement on the AEMU, can achieve sufficient coverage around the suit in all directions. The existing EMU uses a single cavity-type antenna operating between 410 and 420 MHz mounted to the top of the PLSS with satisfactory performance. A similar antenna for the AEMU should be able to satisfy all communications and hardware requirements. If a lower profile antenna such as a flexible antenna or even a conformal antenna is used, then the antenna may be wrapped around various portions of the PLSS and/or portions of the hard upper torso.

Achieving sufficient RF coverage for the high-rate proximity interface at 2.4 GHz is much more difficult for two reasons; propagation at 2.4 GHz is considered quasi-line-of-sight, and the wireless standards for high-rate interfaces generally require a relatively high SNR in order to utilize the higher-order modulation schemes. Operating the high-rate wireless system at 5 GHz is also still under consideration, and that further exacerbates line-of-sight problem. Due to these factors, it is a reasonable assumption to say that the AEMU may need more than one antenna to achieve reasonable performance over the high-rate proximity network.

In order to better understand the RF coverage limitations of a single patch antenna mounted to a person, several simple field experiments were performed that feature a stationary RF terminal designed to emulate a spacecraft or habitat AP and a mocked up EVA antenna. For the first set of experiments, the transmitter consisted of a signal gener-

Figure 2. Mock Spacecraft Access Point with Antenna (on mast) and Laptop (in cab) Shown

ator located inside a pickup truck connected to an omni-directional 2.4 GHz antenna. The generator was powered from an automotive inverter, and the antenna was mounted above the truck on a PVC mast. This setup is shown in Figure 2. The mock EVA antenna was a small 7 dBi 2.4 GHz patch antenna strapped to the author's chest and connected to a handheld spectrum analyzer. The objective of these experiments was to measure the received signal strength at the EVA antenna from a modulated 2.4 GHz signal generated by the signal generator at various distances and orientations in an outdoor environment. The location of this testing was an open field at a city park, shown in Figure 3, which was a relatively quiet radio environment. During testing, several different methods of mounting the EVA antenna to the crew member including steel, aluminum, foil, and foam layers were tested. With this particular antenna, the variations in reception caused by the different mounting configurations were negligible. Received signal strength measurements were read from the spectrum analyzer at 20, 40, 60, 80, and 100 meter distances in three different orientations; facing the transmitter, facing away from the transmitter, and facing perpendicular to the transmitter. The results are shown in Table 3.

Figure 3. Test Site for Antenna Testing

Distance [in m]	**Facing Transmitter**	**Facing 90° Away**	**Back to Transmitter**
20	-40	-52	-63
40	-41	-56	-69
60	-45	-60	-70
80	-45	-63	-75
100	-46	-66	-77

Table 3. Received Signal Strength Measurements (in dBm) for Chest-Mounted Patch Antenna

Orientation	Throughput [Mbps]	Jitter [ms]	Loss [%]
Facing AP	5.00	0.02	0
Side to AP	5.00	0.04	0
Back to AP	1.79	13.80	0

Table 4. IPerf 5 Mbps Test Results (Forward Link)

Orientation	Throughput [Mbps]	Jitter [ms]	Loss [%]
Facing AP	5.00	0.25	0
Side to AP	5.00	0.21	0
Back to AP	1.21	24.34	0

Table 5. IPerf 5 Mbps Test Results (Reverse Link)

6.7 Number and Location of Antennas

The second set of experiments used the same antenna configuration as the first set, but this time netbooks with 802.11bgn adapters were used instead of the signal generator and the spectrum analyzer. An ad-hoc 802.11 connection was established between the AP and the mock-AEMU, and the network throughput, jitter, and user datagram protocol (UDP) datagram loss was measured using the IPerf open-source utility. IPerf was set up to generate and transmit UDP traffic at rates of 5 Mbps and 10 Mbps in both the forward (EVA to AP) and reverse (AP to EVA) directions. Several tests were performed that show how the 802.11 network degrades as the EVA crew member turns their back to the transmitter station, obstructing the line-of-sight between the two antennas. The results of the 5 Mbps and 10 Mbps tests are shown in Tables 4 through 7.

It is clear from both sets of measurements that a second rear-facing antenna would provide a significant benefit to the system. If higher frequencies are to be used instead of 2.4 GHz, a third or possibly even a fourth antenna may be required.

Orientation	Throughput [Mbps]	Jitter [ms]	Loss [%]
Facing AP	10.00	0.05	0
Side to AP	9.68	0.60	0
Back to AP	Complete link failure		

Table 6. IPerf 10Mbps Test Results (Forward Link)

Orientation	Throughput [Mbps]	Jitter [ms]	Loss [%]
Facing AP	10.00	0.21	0
Side to AP	8.93	7.79	1.5
Back to AP	Complete link failure		

Table 7. IPerf 10Mbps Test Results (Reverse Link)

There are several possible designs for RF front-ends that support multiple antennas. The simplest approach is to simply use an RF multiplexer between the antennas and the diplexer so that the same transmitted signal is sent to all of the antennas, and the sum of the received energy is combined as the receiver input. The set of antennas appears as a single antenna to the transceiver. Care must be taken with the cabling and connections to ensure that the antennas are in phase with each other. More advanced RF front-end designs are capable of manipulating the phase and amplitude of each RF channel independently in order to enable beamforming, which is discussed in the next section.

6.8 Currently Available Antennas

In recent years, NASA has funded the development of several AEMU antenna designs, and there are also several other antennas on the market that are suitable for use on the AEMU. Several of these antennas are discussed in this section, while others are omitted from this document in order to protect proprietary information. Additional information about these omitted designs can be provided, if permissible, at the request of the authors.

Pharad, LLC. manufactures a wearable UHF antenna that operates between 350-450 MHz with 0 dBi gain and near-omni coverage. It is vertically polarized, weighs only 2.2 oz, and can handle up to 5 W. This antenna is flexible and designed to conform to a soldier's body armor, and with dimensions of 13 in x 3 in x 0.3 in, the form factor is very similar to the current EMU antenna, but flat and flexible. Pharad also sells a similar models with smaller areas around 4 in x 4 in and gains of -3.8 dBi. It is important to note that while these antennas are promoted as omni-directional, a more important metric is how good the coverage is after the antenna is mounted to the AEMU, which will be the subject of future studies.

A compact planar antenna that operates between 410-485 MHz is described in [Sarabandi]. Although relatively large at around 9 in x 9 in, this antenna has a wider bandwidth than most microstrip patch antennas and a gain of over 5 dBi. In [Murdoch], a 400 MHz circularly polarized antenna array designed for use on micro-satellites is described. The entire array has an area of around 6 in x 6 in, which can be reduced by decreasing the size of the ground plane. Each element of the array is a shorted-patch design with an area of about 2 in x 2 in, but the pattern is very directional and there is only about 3 MHz of useful bandwidth.

At the 2.4 GHz ISM band frequencies and above, patch antennas become physically smaller and more directional. Designs that employ a ground plane are advantageous at these frequencies because the ground plane area is reasonably small compared to UHF and the ground plane reduces the effect of the body of the astronaut on the antenna performance. Due to the large commercial market for RF systems in this band and in the cellular bands, there are a multitude of available low-profile antennas. A comprehensive treatment of this subject is beyond the scope of this paper; instead, the reader is referred to [Cheng] [Ali] [Pasakawee] for a few interesting papers on this subject.

7 MIMO Techniques for EVA

Using multiple antennas at each communications terminal increases the complexity of the hardware and radio electronics, but there are significant advantages. Various performance gains have been realized in commercial wireless systems over the past ten years through the use of MIMO techniques. These techniques tend to fall within three categories: beamforming, spatial diversity techniques, and spatial multiplexing techniques. Beamforming generally involves the use of phased-array antennas, which are most likely not practical for the suit at this time, not required by most WLAN standards, and not widely implemented, so they will not be discussed. The remainder of this section will focus on diversity and multiplexing techniques.

Spatial diversity techniques are designed to increase SNR by exploiting the path diversity that a signal experiences as it propagates along the multiple paths provided by a single-input multiple-output (SIMO), multiple-input single-output (MISO), or MIMO system. These techniques are available for use at the receiver, the transmitter, or both. An example of spatial diversity at the receiver is Maximum Ratio Combining, in which the receiver exploits the differences in amplitude and phase of the received signal at each antenna to better recover the original signal than if only one antenna were to be used. A common spatial transmit diversity technique is the use of Alamouti codes. For more advanced systems, spatial techniques like precoding that use closed-loop feedback mechanisms to pass wireless channel state information between transmitter-receiver pairs could provide even higher coding gains.

Spatial multiplexing is used to increase the throughput of a wireless MIMO system by exploiting the spatial channels that exist between the individual pairs of transmit and receive antennas. In contrast to spatial diversity, the signals that are sent over the spatial channels are independent, so a system with two transmit and two receive antennas will have

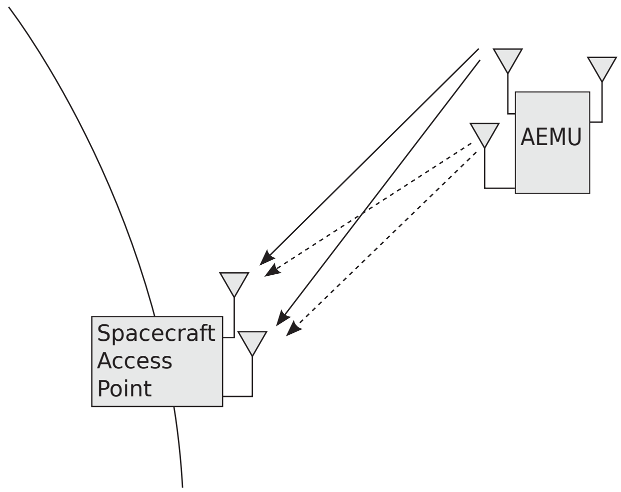

Figure 4. Depiction of Spatial Wireless Channels for EVA

two independent spatial channels, and therefore will provide twice the throughput of a single antenna system. Figure 4 shows a depiction of these spatial channels as applied to the AEMU outside of a spacecraft. The two antennas on the AP and the two antennas on the AEMU that are in sight of the AP allow for two different spatial channels to be utilized. The use of spatial multiplexing is how many modern commercial wireless standards are able to advertise very high throughput rates, although these rates are not achievable without the maximum number of antennas at both the client device and the AP.

Although spatial diversity and spatial multiplexing techniques have an inverse relationship (reliability vs. throughput), they are often used in conjunction with each other. For example, a system will often experience a throughput gain when switching from a spatial multiplexing scheme to a spatial diversity scheme during poor channel conditions. Recent concepts such as linear dispersion codes and spatial modulation provide unified implementations diversity and multiplexing techniques and allow for efficient switching between the two schemes.

This discussion on wireless MIMO is relevant to EVA because the design being considered for the AEMU proximity band is 802.11n with multiple patch antennas mounted around the suit to provide spherical coverage. Since it is likely that two or three antennas will be available along any directional vector to/from the suit, MIMO techniques should be exploited, especially spatial multiplexing. Spatial diversity may not be of great benefit to the suit when operating outside of a spacecraft due to the relatively benign multipath environment. Generally, there are not many objects outside of a small spacecraft for wireless signals to reflect off, so spatial diversity techniques will most likely not provide the same coding gains that can be obtained an in indoor, office-like environment. Spatial multiplexing, on the other hand, will most likely provide

Modulation	Code Rate	20 MHz 800ns GI	20 MHz 400ns GI	40 MHz 800ns GI	40 MHz 400ns GI
BPSK	1/2	6.5	7.2	13.5	15
QPSK	1/2	13	14.4	27	30
QPSK	3/4	19.5	21.7	40.5	45
16-QAM	1/2	26	28.9	54	60
16-QAM	3/4	39	43.3	81	90
64-QAM	2/3	52	57.8	108	120
64-QAM	3/4	58.5	65	121.5	135
64-QAM	5/6	65	72.2	135	150

Table 8. 802.11n Data Rates (in Mbps) for a Single Spatial Stream

significant gains in throughput without requiring more bandwidth or significantly more transmit power. Again, in order for these gains to be realized, there must be multiple antennas both on the suit and on the spacecraft, and 802.11n allows for up to four on each radio. Table 8 shows the various data rates of 802.11n for a single spatial stream. If all four spatial streams are able to be utilized, we can multiply the rates in the table by a factor of four.

8 AEMU Antenna Recommendations

Based on the current state of the art of the AEMU radio design and the opinions of the authors, the following recommendations for the design of the RF antenna subsystem are provided. These recommendations are being used to guide the AEMU technology development efforts currently underway.

In order to support the mission-critical radio band, a single UHF antenna mounted to the top of the PLSS is recommended. This is the same configuration as the current EMU radio antenna and the required performance characteristics are essentially the same, so a new antenna to support this band can be considered a simple performance upgrade. The new UHF antenna should have less weight and volume then the current 1.5 lb 10.23" x 3.50" x 0.75" antenna. Several of the patch antenna designs presented in this paper would be good candidates for consideration, and these antennas should integrate onto the PLSS enclosure in a secure and conformal manner, unlike the current EMU antenna which is attached to the PLSS with Velcro. The high-rate proximity band operating at 2.4 GHz will require 2-3 antennas to achieve reliable spherical coverage around the AEMU. These antennas may be mounted at various locations on the PLSS and hard upper-torso, but there will be other hardware elements such as switches that will be vying for the limited real estate on the front of the torso. Patch antenna technology is also applicable here, but currently the technology is more mature at UHF than S-Band. At both frequencies, the antennas should conform to the relatively flat surfaces on which they will be mounted, but the antennas themselves need not be flexible.

These antenna recommendations are subject to change if there are changes in the overall AEMU communications system design. One likely change that is relevant to the antennas is the shifting of the 802.11 network frequency down to a lower band. By shifting this network down to 900 MHz or even lower, the RF propagation characteristics should improve, possibly even to the point where a single 802.11 antenna can provide adequate coverage around the AEMU. In order for this to happen, NASA will need to allocate at least 40 MHz of bandwidth for this network. Care must be taken so that if this change occurs, the 802.11 network should not be able to interfere with the mission-critical network.

In order to further the development towards a fully functional AEMU communications system, the authors recommend that Agency research and development resources be focused on the following areas:

- Low-profile patch antenna technology, especially at S-Band and higher frequencies
- Efficient and intelligent use of multiple antennas for the proximity band, including the design of the front-end hardware
- Propagation and path loss studies at 2.4 GHz, 5 GHz, and 60 GHz around the AEMU to support the integration of more advanced commercial WLAN technologies into the AEMU and other spaceflight assets
- Packaging and mounting of antennas to the PLSS and hard upper-torso, including the routing of the antenna cables throughout the AEMU.

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Appendix A

Acronyms and Abbreviations

AEMU Advanced Extravehicular Mobility Unit

AES Advanced Exploration Systems

DRM Design Reference Mission

EMU Extravehicular Mobility Unit

EVA extravehicular activity

ISM Industrial, Science and Medical

ISS International Space Station

IP Internet Protocol

LEO low-Earth orbit

MIMO multiple-input multiple-output

MISO multiple-input single-output

PLSS portable life support system

SIMO single-input multiple-output

SNR signal-to-noise ratio

SSCS Space-to-Space Communications System

SSER Space-to-Space EVA Radio

SSSR Space-to-Space Station Radio

SSOR Space-to-Space Orbiter Radio

TDMA time-division multiple-access

UDP user datagram protocol

WLAN wireless local area network