Heterogeneous Spacecraft Networks: Wireless Network Technology Assessment

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Abstract—**Constellations of small satellites are useful for a number of earth observation and space exploration missions. The Heterogeneous Spacecraft Network project is defining operations concepts and promising technology that can provide greater capability at lower cost. Typically, such spacecraft can communicate with each other in orbit and with ground stations for spacecraft operation and downlink of science data. However, small spacecraft often cannot utilize the capability delivered by networks such as the Universal Space Network, even if the mission could afford the cost. Small spacecraft have significant constraints in terms of power availability, attitude stability and overall mass and volume, requiring innovative technology for implementing highly functional satellites. A major challenge for such missions is selecting communications technology able to function in the space environment, able to meet the requirements for both inter-satellite and space-to-ground data links and fit within the resources available on small satellites. Moreover, the cost of the technology needs to be as low as possible to facilitate participation by a broad range of organizations. Finally, the communications networks should conform to standards allowing broad adoption and the use of common infrastructure for multiple missions. Communications technology based on the IEEE 802 family of local area and metropolitan area network standards can be adapted to meet the needs of such missions. This paper will identify possible development paths for improved communication between small satellites and to the ground by reviewing and evaluating standards-based technology for use by small satellite missions. Methods for greatly extending both range and data rate will be proposed and analyzed. It will review and evaluate the IEEE 802.11 wireless network standards, the ITU WCDMA 3G cell phone standard and the IEEE 802.15.4 Personal Area Network standard. A simple set of communication requirements will define the trade offs between standards and identify the technical capability needed for such missions. Specifically, the improvements needed to the Physical Layer to extend range to 1200 Km and the ability to comply with spectrum management constraints will be investigated. Authentication and encryption will be addressed along [1]with adjustments to the Media Access Control layer that can optimize data transfer rates over a broad range of distances and conditions. The paper concludes with recommendations for standards-based communication technology development for small satellites supported by the results of this trade study. The primary objective is to greatly reduce the cost of data communication for small satellites by establishing a common infrastructure able to meet the needs of most missions.**

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1. INTRODUCTION

Small satellites offer advantages in terms of cost and launch opportunities. CubeSats based on the standards defined by California State University at San Luis Obispo offer educational opportunities for aerospace engineering students as well.[1] These spacecraft often use UHF beacons or RF modems operating in unlicensed Instrumentation, Scientific and Medical bands (ISM) around 900 MHz and 2.4 GHz. This paper studies the use of wireless network standards for both space-to-ground (S-G) and space-to-space (S-S) communications for missions consisting of a constellation of small satellites. Improvements in communications capability can be realized by upgrading the communications link to higher performance using openly available standards such as IEEE 802.11 and commercial hardware and software from numerous manufacturers.[2] This could lead to a network of compatible ground stations able to support small satellite missions at low cost while delivering high overall performance and able to be used by a large range of organizations–the vision for Heterogeneous Spacecraft Networks (HSN).

The HSN project is developing a concept for low-cost operation of small satellites in LEO where multiple organizations can collaborate using the Internet and emerging Information Technology like Cloud-based resources. The HSN project is evaluating standards and performing network simulations to validate the proposed technology. Three papers help define the overall vision, including this one. The first paper covers the Operations Concepts proposed for HSN.[3] The other paper covers performance simulations for hybrid networks.[4]

This paper covers three standards for terrestrial communication applied to space communication at the Physical and Media Access Control Layers. It focuses on the requirements for small spacecraft communication, the standards and technology available and the engineering tradeoffs involved in deciding which standards and products to employ for an actual mission. It reviews the current practice and state-of-the-art and looks at the limitations of wireless network technology for addressing space communications and most importantly, what simple improvements can be made to extend the existing capability for space use.

Radio modems based on proprietary protocols such as the Microhard MHX2400 have been used for CubeSat missions such as OREOS.[5] They operate in the 2.4 GHz ISM band and can meet FCC requirements when operated by a University or other private entity. They generally use dedicated ground stations set up specifically for the mission. Another approach is the use of UHF beacons or even UHF-band radio modems for high-performance. The UHF beacon approach generally uses a network of amateur radio operators for receiving the signals and interpreting the low-rate data.[6] For high data rates, the OSAGS mission used a network of special ground stations ultimately capable of delivering 100 Mbps from three sites and represents the best effort to date.[7] Most of these solutions are point-to-point communication systems, and cover a wide range of missions and costs.

NASA Ames Research Center, under the Edison and Franklin Programs, initiated a trade study that looked into the use of WiFi IEEE 802.11 communications for CubeSats in LEO.[8] This paper goes further in evaluating and comparing other standards such as Personal Area Networks (PAN) (IEEE 802.15.4) technology such as ZigBee and 3G cell phone standards based on Wideband Code Division Multiple Access (WCDMA) protocols. These technologies use the unlicensed ISM band, or similar licensed bands and the standards are flexible enough to meet diverse requirements.

2. COMMUNICATION REQUIREMENTS

Small satellites have physical size constraints that prevent the use of large high-gain antennas. They also have low power solar arrays and small batteries; so they will only support small transceivers. In fact, the power available is so low as to require the use of duty cycle limits for communications. Moreover, the use of directional antennas to improve link margin and increase range requires some attitude stabilization for pointing, a feature not found in many small satellites.

Small satellites are often built and operated by organizations such as Universities that do not have large financial resources to conduct missions. Therefore the availability of low-cost technology and its utility for serving multiple missions are truly advantageous. By looking at various small satellite missions either flown or proposed, a reasonable set of requirements can be created that allow evaluation of standards and technology able to meet them.

One key requirement would be range, in terms of the overall distance between communicating objects, either between spacecraft (S-S) or between the spacecraft and the ground (S-G). For LEO missions, 1200 Km is a good working figure for the S-G link, providing good coverage to reasonable altitudes of about 600 Km. For the S-S link, 200 Km would be a good figure for most constellations deployed during a single launch. These numbers come from various mission designs and represent an average of anticipated requirements.

A large dish is needed on the ground, providing gain for increasing range. These vary in size from 1 meter to about 35 meters in diameter, with the larger dishes having a very narrow beamwidth requiring significant point accuracy to see the spacecraft in orbit. A 3 meter diameter dish producing about 35 dBi in gain is assumed for the ground station antenna. This dish will require highly accurate tracking to follow the spacecraft as it passes overhead once every orbit with pointing accuracy within one degree. The latitude of the ground station is equally important. For low-inclination orbits sites near the equator have significantly greater coverage, but for sun-synchronous orbits ground station sites near the poles are better. This paper makes no assumptions regarding location of the ground station, but does assume a fixed antenna size and a compatible transceiver.

The power available on the spacecraft is also a known quantity. For 1.5U Cubesats for example, 15 W peak can be sourced for a few minutes, with less than 1 W available continuously for the communications subsystem. The 15 W peak power produces about 1W of RF transmit power to the antenna for most transceivers operating at 2.4 GHz. The antenna has a gain of about 1.5 dBi for a dipole or quadrapole radiator and about 5 dBi for a directional patch antenna. These types are typically used for CubeSats and the 5 dBi patch is assumed for the spacecraft antenna, which needs some degree of attitude stabilization for pointing.

3. EVALUATION METHOD

This paper will cover the two lowest levels of the OSI network model, the Physical (PHY) layer and the Media Access Control (MAC) Layer, which controls link access and data flow. The primary objectives are to define PHY or

radio characteristics useful for small satellite missions such as transceiver type, transmitter power and antenna configurations based on the proposed standards. The spacecraft transponder and the ground station characteristics will be described, leading to a complete solution. The range and data rate are the primary quantitative comparison factors. The cost in terms of spacecraft size, weight and power consumption (SWAP) will be estimated as a qualitative Figure of Merit (FOM) in the analysis. Most 802.11 wireless network standards use spread-spectrum for radio communications, which differs from narrow-band communication and requires special analysis. This paper presents a first order analysis of the effect of spread spectrum techniques when applied to space communications and quantitatively compares the performance of each standard.

The corresponding MAC layer protocols also determine a given standard's applicability for space mission operations. The MAC layer handles association and authentication of nodes, as well as low-level data flow control. Most MAC standards support simultaneous multi-way communications, a key attribute of networks. The MAC layer is the key for establishment of spacecraft networks, either between each other in orbit, or to multiple ground stations. The MAC layer turns point-to-point radio links into a capable network using access control and data link control mechanisms specific to each standard. The different standards provide support for different topologies and require different methods for network establishment and fault management. For example, WiFi uses either an access point or can communicate directly between two devices, while ZigBee creates ad-hoc hierarchical PANs. The resultant data rates under realistic conditions are a key figure of merit (FOM), along with the network topologies supported, the method of association and authentication and the ability to juggle many concurrent links under realistic orbital conditions. These attributes will be included in the table of FOMs used to compare the standards.

The analysis will consist of a basic link margin analysis where the PHY layer is implemented in a pragmatic manner using available antenna technology and within spacecraft SWAP constraints. Theoretical versus typical values are compared for each standard and include the effects of spread spectrum modulation. The transceiver and antenna characteristics are defined by looking at the current product lines available in the commercial market. Moderate ground station antenna size is highly desired, driving the solution trade space. The constraints on spacecraft power in particular pose interesting challenges for link management. A table of the overall benefit of each standard will be constructed using the derived FOMs.

Space-to Ground Segment

The primary link is the one from the spacecraft to the ground station, which allows mission operators to receive telemetry from the spacecraft, send commands and to collect payload data. The ground station is almost always a parabolic dish, which provides significant gain along precise directional beams over a large range of frequencies. Dishes can range in size from 1 meter to over 70 meters in diameter for the large Deep Space Network antennas. A one meter dish will work for LEO, while a 70 m dish will receive signals from the edge of the solar system. The corresponding gains are 10 dBi and 63 dBi (at 2.4GHz) respectively.

For a parabolic dish, the gain scales with dish size using the following equation:

$$G\ (\text{numeric}) = \pi^2 d^2/\lambda^2 \qquad (1)$$

where d is diameter in meters and λ is the wavelength. An efficiency factor needs to be applied, in the range of 0.6 to 0.9 to get actual performance and the numeric value is often expressed in dB.

The corresponding beamwidth is given by:

$$\theta\ (\text{degrees}) = 70\lambda/d \qquad (2)$$

For a 3 m dish, the gain is 35 dBi with a beamwidth of 3 degrees and this is our reference configuration for the trade study.

The space to ground (S-G) link must be robust and reliable, as mission success depends upon it. There is also a correlation between a spacecraft's orbit and the location of the ground station on earth, which sets the schedule for satellite data access and duration, commonly called a communications pass. For example, a low inclination LEO mission would use ground stations near the equator, while a sun-synchronous polar orbit would favor ground stations near the poles. These alignments produce the highest duration and frequency of communications passes for these types of orbits.

The ground station does not have the same constraints as the spacecraft. For example the parabolic dish antenna can be much larger and the transmit power and duty cycle much higher. This can increase range and data rate, but can result in asymmetrical characteristics for the link. Due to spacecraft transmit power limits, the downlink can be less powerful than the uplink. Also, the dish antenna needs to track the spacecraft. A skilled team of radio engineers, a significant cost factor, usually performs tracking and acquisition of the spacecraft signal. Automation of antenna tracking could significantly reduce overall ground station operational cost, while increasing antenna cost, and will be considered. An array of sector antennas is a possible alternative, based on the cell phone tower approach.

The spacecraft antenna usually has directional response, as indicated by its radiation pattern. The radiation pattern must be pointed toward the earth station within the beamwidth of the antenna to support communications. This drives requirements for spacecraft attitude stabilization and pointing. Omni-directional antennas like monopoles or dipoles produce wide toroids and multi-element quadrapoles

create a non-symmetrical spherical pattern. Higher directionality results in higher gain, but this drives pointing accuracy higher as well. To accurately point its antenna, a spacecraft must have a reasonable idea of its orbital position and the location of the ground stations.

Attributes of the S-G link would be antenna gain, beamwidth and pointing accuracy, and maximum range. The transmit power, antenna gain, free-space loss and receiver sensitivity determine the resulting link margin.

Space-to-Space Link

In contrast space-to-space (S-S) links are between spacecraft in orbits where they have direct line-of-sight with each other and are within range of the communications links. Unlike S-G links, it is difficult to have a large dish on a small spacecraft, so range will be much shorter. Transceiver power is also limited, further reducing maximum range. Finally, directional antennas need to be pointed at the other spacecraft, so orbit knowledge and precision attitude control is needed as well for effective S-S communications. The broad patch antenna used as our reference design has 80 degrees of beam width so that simple passive attitude stabilization might suffice.

Range of operations scales indirectly with data rate. Each doubling of data rate represents a loss of 3 dB in link margin, reducing range by a factor of 0.7. Therefore, this general rule-of-thumb can be used to estimate the range provided using higher data rates. For S-S links, the distances are generally much shorter than S-G, so data rates can be correspondingly increased under many circumstances.

Connection Models

One key aspect for multi-way link use is to understand the connection topologies supported by the various standards. These progress from point-to-point, to star and tree type topologies. See the diagram below.

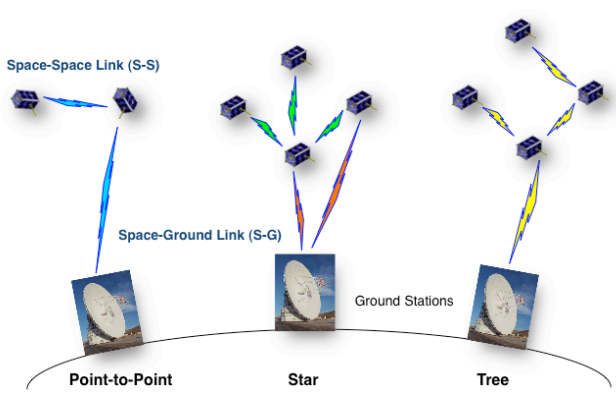

Figure 1. Communication Network Topology

Most space communication links conform to the point-to-point (P2P) model, that is, from a single spacecraft to the ground station, or from one spacecraft to another as shown in the leftmost diagram. Moreover, most RF links really only send data point-to-point, simulating multi-way links by sending packets sequentially using time slots to create the illusion of concurrent connections. Radio modems, Bluetooth and WiFi 802.11 in ad-hoc mode are examples of point-to-point networks. The blue links in the diagram correspond to the S-G or S-S links respectively. Addressing is also point to point, where the ground station specifies the MAC address of the spacecraft it wants to communicate with.

A good example of the star configuration is WiFi operating in infrastructure mode, with the access point acting as the central point or hub of the star. All wireless access is mediated and coordinated by the access point. All client nodes must see the access point in order to participate in the subnet. In the middle diagram, either the ground station or a selected spacecraft functions as the hub of the star network. The orange links would allow communication with multiple spacecraft (within the beamwidth of the antenna) with the ground station as the hub. The green links represent the case where a given satellite is the hub, able to communicate with all other satellites within range. Star networks often support handover from one hub to another, called roaming, implemented in WiFi and 3G. Cell phone networks have a similar topology, with the cell phone tower as the central node. Due to the complexity of the cell phone hub, it is likely only to be resident on the ground station.

Finally, the tree network configuration is very similar to wired Ethernet with multiple subnets connected to a router. It forms a network from a "root" node and creates a tree with many branches forming from each node. The root node forms the network and often provides the gateway to other networks like the Internet. The intermediate nodes often support routing functions to the end-point nodes, which act as the leaves of the tree. Tree networks often incorporate mesh routing to enhance data delivery reliability and extend the overall range of the network through routers acting as repeaters. The rightmost diagram shows the approach with either the ground station or a selected satellite acting as the root and each configuration looks the same as represented by the yellow links.

Which network topology is best? This depends upon the desired mission configuration, the number of satellites and ground stations, the separation between the spacecraft and the amount of data throughput needed. Point to point is the only solution for most simple missions where there are simply not enough nodes to create any other type of network. Star topology would be best for networks where a central node, often the ground station, desires to communicate with multiple spacecraft located in close proximity, like a closely coupled cluster of satellites. The tree topology is best for complex missions, as it supports both ad-hoc network formation and automatic routing of data.

4. STANDARDS COMPARISON

Three standards, a wireless general purpose network based on the IEEE 802.11 standards, a wireless sensor network based on IEEE 802.15.4 and ZigBee and a cell phone network based on the ITU 3G WCDMA standard are compared below.

802.11 WiFI

The WiFi family of standards consists of the IEEE 802.11, 802.11b, 802.11g and 802.11n methods, each using either Frequency Hopping Spread Spectrum (FHSS) or Discrete Sequence Spread Spectrum (DSSS) modulation for co-existence with other WiFi networks. They all use the 2.4 GHz ISM band and just vary in the exact type of modulation, the amount of frequency spectrum utilized and their resultant data rates. The 802.11b standard uses CCK and QPSK modulation, while the 802.11g standard uses Orthogonal Frequency Division Multiplexing (OFDM). 802.11n is just 802.11g using a wider range of the ISM band and Multiple-In-Multiple-Out (MIMO) antenna technology to deliver up to 300 Mbps of raw data rate. The FCC limits these devices to an Effective Isotropic Radiated Power of 1 W.

WiFi uses the SSID parameter to identify the network and devices with the same SSID either connect to an Access Point for Internet access (infrastructure mode) or can use ad-hoc mode to setup direct connections with each other. The MAC layer works by using Carrier-Sense Multi-Access (CSMA) for arbitrating access to the wireless medium, in effect juggling multiple connections at the packet level. A beacon packet is used for coordinating the network, periodically determining network membership and assigning time slots for better utilization of the medium. All data transfers are direct from source to sink, with the access point only coordinating the transfers. It is essential that all the nodes of the network receive and respond to the beacons from the access point. Ad-hoc mode uses the exact same methods of media access, but does so only on a point-to-point basis. Even the beacons are point-to-point, as are the means of establishing a connection. Ad-hoc mode is more flexible, but is less effective at managing overall network throughput. These networks create data packets that resemble Ethernet and usually use TCP/IP or UDP protocols for user data transfer.

Management of the SSID names can help configure dynamic networks with multiple members. The MAC supports secure authentication and link encryption by exchanging keys upon association. For infrastructure mode, the device requests association using a given SSID, the access point allows association if the SSID matches its own SSID, and then can proceed to authentication, where passwords and encryption keys are exchanged and checked.

The resulting topologies are either a star network or a collection of point-to-point links. WiFi can support space-to-space links using ad-hoc mode. If the ground station is an access point in infrastructure mode, the ground station is the central node of the star and can actually support connections to multiple satellites simultaneously, which could improve overall mission throughput considerably.

For longer distances, the MAC timing has to be adjusted to account for the much longer latencies produced by light speed delays. Several papers have been written about how to accomplish this. Basically, the interpacket and interframe spacing needs to be increased for longer distances.[9]

For this paper, we only evaluate 802.11b running at the lowest data rate of 1 MHz. This represents the best case in terms of range performance, with the other variants providing significantly higher data rates, but with significantly shorter range.

IEEE 802.15.4 and ZigBee

The IEEE 802.15.4 standard for Personal Area Networks (PAN) was created to support low-power sensor networks. The ad-hoc protocols for network formation produce trees consisting of full-function devices (FFD) capable of routing data and reduced function devices (RFD) generally producing the data from sensors. The root node is called the coordinator, and is necessary to initiate network formation. Once a network is formed, the coordinator can then act as the network gateway to terrestrial wired networks. Routers can also act as gateways, but RFDs cannot.

The ZigBee protocol, running above the 802.15.4 layer uses Ad-hoc On-demand Distance Vector (AODV) routing to support mesh networks where intermediate routers support dynamic network configurations and route data through the network despite changes in the physical layout. Superior routing and ad-hoc formation are key advantages for missions where large numbers of satellites gather large amounts of data.

The MAC is also based on CSMA like 802.11 but the data packets do not look like Ethernet frames. The ZigBee protocol supports either profiles or applications providing a rich environment for customization of MAC functions and adjustment of key parameters. The ZigBee framework provides support for application programs that can help create templates for ease of software porting and extension of function. It is anticipated that similar changes to the MAC-layer timing would be needed to adapt the network timing to the longer distances required for space use, much in the same manner as for 802.11.

The typical mission configuration might consist of a collection of spacecraft, with the smallest supporting RFD nodes and the intermediate ones using FFD. Small spacecraft can be used to gather data, storing it temporarily until within range of another FFD spacecraft that can act as a router. The FFD is also able to downlink data to the ground station. The RFD nodes collect data; send it to the FFD nodes, which in turn downlink to the Ground Station during a communications pass. Therefore much of the

functionality involved with Delay Tolerant Networking is embedded in these MAC-layer protocols.

3G WCDMA

Wideband Code Division Multiple Access (WCDMA) is commonly known as 3G for cellphone data transmission as an ITU standard and may be particularly useful for small satellites. Unlike the other standards (many of which are part of 4G upgrades), this standard is designed for longer haul on the order of several miles at power levels of about a watt or two. The spreading function occurs over a smaller bandwidth, greatly increasing sensitivity by limiting thermal noise. The lower data rates (12 Kbps) result in high processing gain, also increasing sensitivity by effectively lowering the noise floor. Typical receivers are orders of magnitude more sensitive than WiFi transceivers as a result, with important caveats. For high rate data transmission (384 Kbps), the range is greatly reduced by a factor of about -10 dB, resulting in range comparable to WiFi. Moreover, while the cell tower transceiver has high sensitivity, (-121 dBm) the mobile transceivers have -4 dB less sensitivity (-117 dBm), reducing range for spacecraft transceivers. Finally, the cell tower transceivers can use up to 2 W of RF transmit power, while the mobile transceivers range between 0.1W to 1 W output power. This standard also requires use of licensed spectrum in the 1.9 and 2.1 GHz bands.

The MAC layer handles call management using cell phone protocols. This again creates a barrier to easy adoption, as these protocols are very specialized and are not directly TCP/IP compatible.[10] In general, circuit switched (voice), packet switched (data) and control plane data are handled on multiple channels. The data rates can vary from 12.5 Kbps for voice to 384 Kbps for data traffic and multiple rates can be supported simultaneously, but with widely varying link range and quality. The link is also assymetrical at high data rates, with uplink to the base station much slower. The 3G MAC complexity is beyond the scope of this paper so will not be evaluated specifically. A large level of effort is anticipated for adapting these protocols to HSN use for spacecraft communications.

An interesting feature of cell phone towers is the use of multiple sector antennas covering a full 360-degree plane perpendicular to the tower for terrestrial use. Imagine turning the cell tower on its side, and aiming the multiple sectors skyward. The automatic antenna switching capability could be used to create a tracking ground station without the use of electromechanical components. Since much of the engineering has been done, it is more a matter of adapting this work to space use.

5. SPREAD-SPECTRUM ANALYSIS

Most space communications is based on narrow-band signals containing a modulated data stream, where the bandwidth used is not a significant proportion of the carrier frequency. For example at a 2 GHz carrier frequency, the deviation caused by modulation would be a few megahertz. These signals carry the farthest for a given transmit power and it is easy to build high-sensitivity receivers using resonant circuits. Wireless network and cell phones by contrast use spread-spectrum communications for their radios, spreading the overall bandwidth required significantly in order to promote harmonious co-existence of multiple radio systems within the same geographical area. The chief benefit of spread spectrum is low detectability and high immunity to interference. For wireless networks, the interference immunity is the main reason the standards all require the use of spread spectrum.

There are various types of spread-spectrum, such as Direct Sequence (DSSS) or Frequency Hopping Spread Spectrum (FHSS) or Orthogonal Frequency Division Multiplexing (OFDM), all relevant to wireless network standards. Our first-order analysis applies to DSSS radio systems and we compare WiFi 802.11b to WCDMA and to ZigBee based on the IEEE 802.15.4 standard.

The effect of spread spectrum, where the main carrier is modulated by a spreading function prior to having the data modulation added, is to increase the bandwidth of the carrier signal, necessitating a wide bandwidth receiver front end. Since receiver sensitivity is limited by thermal noise and is proportional to input bandwidth, spread-spectrum receivers have lower overall input sensitivity.[11] This is given by:

$$N_t \text{ (dBm)} = 10\log(KTB_{rf}) \quad (3)$$

where K is Boltzmann's constant, T is temperature in K and B_{rf} is input bandwidth.

The Processing Gain (PG) is the ratio of bandspread to data rate and is given by:

$$PG(dB) = 10\log(B_{rf}/R_{bit}) \quad (4)$$

where R_{bit} is the effective data rate

The Processing Gain is applied to the input noise, effectively lowering the noise by the PG value. A certain signal to noise ratio results in a certain bit error rate (BER) and this varies dependent upon exact modulation and spreading function. However, an average can be used, so 5 dB is chosen based on the characteristics of the chosen transceivers. The proper combination of these values can yield the theoretical maximum input receiver sensitivity R_t (limited by thermal noise) as given by:

$$R_t = N_t + PG - Eb/No \quad (5)$$

Moreover, the standards often specify a minimum implemented receiver sensitivity and typical products can conform to or exceed these values. Note that actual sensitivity can never exceed the adjusted thermal noise limit. The results of these calculations are summarized in the table below.

Table 1. Spread Spectrum Characteristics

PARAMETER	WiFi	WCDMA	ZigBee
Frequency (MHz)	2450	2100	2450
Data Rate (Rbit MHz)	1	0.012	0.25
Chip rate (Brf MHz)	11	3.84	2
Proc Gain (dB)	10.41	25.05	9.03
Thermal Input noise (dBm)	-103.56	-108.13	-110.97
Maximum Bit Error Rate (BER)	1.00E-03	1.00E-03	1.00E-03
Required Eb/No (dB)	5	5	5
Effective Noise Floor (dBm)	-113.98	-133.19	-120.00
Theoretical Receiver Sensitivity (dBm)	-108.98	-128.19	-115.00
Allowable Noise Factor	28.98	7.19	30.00
Specified Recv. Sens. (dBm)	-80.00	-121.00	-85.00
Typical Recv. Sens. (dBm)	-95.00	-117.00	-98.00

The main figure of merit is the theoretical receiver sensitivity, which determines the ultimate limit for link performance using the specified standard. However, the specified receiver sensitivity and the typical receiver sensitivity are equally relevant since they are the best indicators of actual performance. The Specified Receiver Sensitivity is the minimum sensitivity that complies with the standard. The Typical Receiver Sensitivity is the sensitivity of representative products that conform to the standard. The most relevant parameter for actual performance is the Typical value. The Theoretical value can be used to determine how much improvement is possible using low-noise preamplifiers.

One exception is that WCDMA specifies two different values for sensitivity, one for the base station in the cell tower and the less sensitive one for mobile handsets. The mobile handset number is used for the Typical value, since it is representative of the spacecraft transceiver. The cell tower transceiver value would be used for the ground station.

The interference rejection is provided by the spreading function, so wider spreading produces better interference performance. The numbers show that WiFi and ZigBee are fairly equal in interference rejection with WCDMA providing just about one quarter the interference rejection. High interference rejection provides the capability of either running in high noise environments, or having many wireless subnets running simultaneously. Since WCDMA access is moderated by the code division access protocol, it does not need as much interference rejection in the PHY layer as CSMA access protocols.

Using the table above, the best choice for long range is WCDMA, followed by 802.15.4 (ZigBee) with WiFi taking up the rear. The difference between ZigBee and WiFi is about a factor of two. These results are consistent with known and measured link performance and will be used in the link margin calculations to produce the representative FOMs for range.

6. Physical Layer Link Margin

One must be able to receive the RF energy and interpret its information content. This requires the received signal to be demodulated properly after traveling through space (free space loss) and in the presence of noise (noise floor). Only when the signal strength is greater than the receiver sensitivity can the information be decoded. There is a direct relationship between received signal strength and bit error rate (BERR) or packet error rate (PER). Generally a margin of + 5dB results in an acceptable BERR of 10E-5 or 1 error in 10E5 bits of data. Note that this is a high error rate, so even greater margins are needed for robust links.

The effect of data rate is that for each doubling of data rate, there is a concurrent loss of 3 dB of link margin because the signal required for providing a given error rate needs to also double. The parameters required for link margin calculations are generally NOT available from the chipset manufacturers. Instead, the manufacturers specify the resultant receiver sensitivity for each of the modes supported by the chips. The link margin tables summarize this data as the Typical Receiver Sensitivity value culled from numerous communications chip providers.

The table below outlines the anticipate performance of each standard using a 3 m dish (35 dBi gain) for the ground station and a wide-angle patch antenna (5 dBi gain) for the spacecraft. Polarization, rain and pointing losses are typical for DSN operation. Both the maximum range and the typical range calculations are shown.

Table 2. Typical Space to Ground Link Margin

PARAMETER	WiFi	WCDMA	ZigBee
Frequency (MHz)	2450	2100	2450
Data Rate (Mbps)	1	0.012	0.25
Gnd Transmit Power (Watts)	1	1	1
Gnd Transmit Power (dBms)	30.00	30.00	30.00
Gnd Antenna Gain (dBi)	35	35	35
Gnd EIRP (dBm)	65.00	65.00	65.00
Gnd pointing loss (dB)	-0.02	-0.02	-0.02
Range @ Elevation Angle (km)	750	18,000	2,400
Free Space Loss (dB)	-157.73	-184.00	-167.84
Atmospheric Loss (dB)	-0.1	-0.1	-0.1
RIP @ Spacecraft Antenna (dBm)	-92.85	-119.12	-102.96
Spacecraft Antenna Gain (dBi)	5	5	5
Spacecraft Receiver Sensitivity (dBm)	-95	-121	-105
Basic Link Margin	7.15	6.88	7.04
Polarization Loss (dB max.)	-1.26	-1.26	-1.26
Pointing Loss (dB)	-1	-1	-1
Rl, Rain Loss (dB)	0	0	0
Modulation Loss (dB)	0.00	0.00	0.00
Implementation Loss (dB)	-2	-2	-2
Total Loss (dB)	-4.26	-4.26	-4.26
Resultant Link Margin (dB)	2.89	2.62	2.78

The table confirms that the links with the greatest receiver sensitivity also have the longest range. What is most interesting is the spread between the theoretical range and the typical range for each standard. Better engineering of receiver front-ends or the use of low-noise preamplifiers can improve the performance by moving the range from the typical toward the maximum values. So the spread represents the level of improvement that is available for increasing range. The primary FOM is the range values and WCDMA is at the top, followed by 802.15.4 and finally 802.11b. Our goal is to support 1200 Km links, which can be achieved at low data rates using ZigBee or WCDMA, but not WiFi. Only WiFi engineered to improve receiver input sensitivity could meet this goal.

The Space-to-Space link margin calculations are the same as the Space-to-Ground case, but with a much lower gain antenna combination using the 5 dBi patch to 5 dBi patch antennas. The range is reduced to only a few dozen kilometers. Again, the results as shown in the table below conform to the earlier results, with WCDMA being the best. The most representative FOM is the Typical Range available, but the table lists the Maximum Range and the Specified Range for completeness. Only WCDMA and ZigBee can meet the range objective.

Table 3. Space-to-Ground and Space-to-Space Range

Range from Link Margin	WiFi	WCDMA	ZigBee
S-G Max Range - Km	3500	35000	7000
S-G Typical Range	750	17500	1050
S-G Specified Range	130	17500	230
S-S Max Range	120	1250	240
S-S Typical Range	24	550	33
S-S Specified Range	4	350	7

7. FIGURES OF MERIT

Comparing these wireless network standards is like comparing apples and oranges as each one is intended for a different purpose with certain features that cannot be directly compared. Therefore Figures of Merit (FOM) will be used to help define the specific trades involved with choosing the right standard for the intended mission. Certain figures such as range, link margin and data rate are quantitative, while the others such as SWAP are qualitative. Key qualitative FOMs are the connection models supported by the standard, the availability of hardware and software components and other features. Licensed spectrum is also an attribute of relevance.

Table 4. Quantitative Figures of Merit Comparison

FOM	WiFi	WCDMA	ZigBee
S-G Range (Km)	130-3500	5000-35000	230-7000
S-S Range (Km)	4-120	10-1250	7-240
User Data Rate (Kbps)	500-5,000	12-160	120

One desires maximum link margin at minimum transmit-mode power consumption for highest efficiency. The link margin calculations show that WCDMA is the most effective method in terms of PHY layer performance, mostly due to its low data rate. It will easily meet the 1200 Km range requirement. Note that carrying higher-rate data will make the WCDMA ranges similar to WiFi as represented by the lowest numbers for WCDMA. Neither WiFi nor ZigBee will typically attain the 1200 Km range required, but with a low-noise pre-amplifier or better chipset it should be just possible to meet the goal. Note that the higher data rates such as 802.11b at 11 Mbps, 802.11g or 802.11n would not work at this range.

Another key FOM is the overall data throughput that can be supported. WiFi supports the greatest data rate, with ZigBee and WCDMA providing similar data rates. Note that the impact of higher data rate on link margin is significant, lowering range greatly. For example, WCDMA will perform similarly to ZigBee if providing data at 384 Kbps.

Table 5. Qualitative Figures of Merit Comparison

FOM Description	WiFi	WCDMA	ZigBee
Topology	P2P/Star	Star	Tree
Routing	No	No	Mesh
Authentication	Yes	Yes	Yes
Encryption	Yes	Yes	Yes
TCP/IP support	Yes	No	No
Cost	Low	High	Med
Open-source SW	Yes	No	No
Automation	Pointing	Sector	Pointing
Duty Cycle Limit	Med	Med	Low
Interference Rejection	High	Med	Med
Licensed spectrum	No	Yes	No
Power Draw	Med	Med	Low
Volume	Low	Med	Low
Mass	Low	Med	Low

The qualitative FOMs allow capturing features that cannot be expressed or compared quantitatively, but that are also important for trade studies. Open-source MAC software appears to be only available for WiFi currently. This favors WiFi in terms of component availability. The Z-stack or comparable software framework for ZigBee is a licensed software product, but allows user access to low-level features. One often gets the development license at low cost. The cost of WCDMA software is unknown and given the complexities of the MAC layer, the highest cost is probably the learning curve.

All networks discussed support secure authentication and link encryption of varying quality. It is important for all satellite links to have at least a basic level of security and most standards incorporate the basics.

WiFi and WCDMA support star networks, while ZigBee supports tree networks. Tree networks are supersets of star networks. There is difficulty implementing S-S links with WCDMA, as the connection protocol is complex and generally relies on a high-performance base station, hard to implement on spacecraft. Therefore this standard is best for S-G. If multiple spacecraft are in the beamwidth at the same time, then the ground station acting as the hub for the star can communicate with multiple spacecraft simultaneously. For WiFi in infrastructure mode, this can also be used for very effective space-to-space communications, but only while multiple spacecraft are in the ground station beam.

The routing capability is important because mesh routing, where intermediate nodes automatically forward data to an outlying node, can greatly increase effective range by using a number of hops. In this case, ZigBee incorporating mesh routing at the MAC layer is the clear winner. The others do not incorporate any routing features in their MAC layers.

However, routing is often accomplished at the network protocol layer or even in the application layer. Solutions such as Delay Tolerant Networking (DTN) can be used with any of the communications links.

Two types of ground station automation are considered: the first is using electromechanical actuators to physically point the antenna using a-priori knowledge of spacecraft orbit. This is similar to the method used for most ground stations, but substitutes control loops and computers for the human team. Many such ground stations are available, although few used for small satellites due to cost. The WCDMA technology presents an interesting ground station automation solution. Since cell phone towers already steer the RF energy to multiple sector antennas located around the tower, this technology already supports antenna beam steering using an array. This eliminates the mechanical aspects of automating ground stations, and in addition this approach does not require orbital knowledge. The spacecraft sends a signal to the ground station, which automatically selects the correct sector to use. More work is needed to evaluate this option.

The duty cycle for communications is another FOM of particular importance to small satellites, where power consumption is the major operating constraint. ZigBee node can sleep once a network is formed, waking for only the time needed to send a data packet. This results in extremely low duty cycles for transmission, which lowers power consumption significantly and is another major factor favoring ZigBee. The other two standards require connection management (create or re-initiate a connection) prior to sending a data packet. This connection management can actually consume quite a number of cycles and packets and could actually cost more power than the actual data transmission. Both WCDMA and WiFi protocols assume the node is always powered up and able to respond to beacons. While WiFi and cell phones can sleep, they actually have to reconnect to the network after waking.

Interference rejection is important for concurrent use of communications links or operation in noisy environments. All three standards do well in this regard due to the use of spread-spectrum modulation, with WiFi having the best rejection. Spectrum management is another FOM. The use of ISM bands allows Universities to operate ground stations without a license, but different rules apply for different operators. For example, the carrier frequency for ISM standards can be shifted to a licensed S-band supporting a broader range of missions such as those operated by the US Government. For certain chipsets, this might be as easy as shifting the basic clock frequency. WCDMA uses the 1.9 and 2.1 GHz licensed spectrum set aside for cell phone use. Therefore this standard would require the use of licensed spectrum, and this is probably owned by an entity with terrestrial interests, not necessarily interested in allocating a portion to HSN. In fact, potential interference with cell phone networks is probably a significant issue.

The availability of components and software often drives cost. The lowest cost solutions are also the most commonly used but have the lowest overall performance. The WCDMA hardware could be affordable if one uses a cell phone tower development environment to adapt the system to HSN use. Most solutions are very low SWAP, consisting of a couple of chips and the antenna.

8. CONCLUSIONS

The analysis was consistent in terms of expected performance and resultant FOMs provided by each standard. The standards were chosen to fit broad anticipated mission needs, so any of the standards could be applied to actual mission designs, but the analysis shows that certain standards work best for specific types of missions. For example, if a mission needs longer range, but requires relatively low data rates, then WCDMA is the best choice. For closely coupled clusters of satellites requiring significant information exchange, the use of WiFi networks would be best. The respective trade-offs are also important, with the WCDMA solution requiring the most development and the WiFi solution requiring the most on-board power.

The PHY Layers of each standard are similar with WCDMA providing the best performance in terms of range, mostly due to low data rate and limited spreading. WiFi provides the best performance for high data rates. ZigBee fits very well into small sat missions with many spacecraft where mesh routing can improve range significantly. The most intriguing result was the consistency of the PHY layer analysis. For a given data rate, the range would be similar, due to the similarity of the spread spectrum techniques.

The MAC Layers differ significantly, with WiFi supporting both star and P2P topologies. The persistent network connections offered by WiFi is useful for closely coupled clusters where high data rate contributes to overall performance. WCDMA only supports star configurations due to its dependence upon a central node and this limits it to S-G use. Zigbee networks support ad-hoc dynamic tree configurations and this is considered a key advantage for complex missions consisting of many spacecraft. The ZigBee protocol supports very low duty cycles, which makes it the ideal choice for sending small amounts of data at periodic intervals from very small spacecraft.

In the short term, WiFi can work for small constellations with the appropriate adjustments to PHY and MAC layer. In the longer term, self-configuring networks will provide significant advantages. The use of cell phone technology for implementing the S-G link is particularly attractive due to its high performance and the potential of using switched sector antennas to implement an automatic ground station requiring very little human intervention, a key attribute for HSN. We will continue on a dual path of developing and evaluating communications subsystems based on multiple standards.

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BIOGRAPHY

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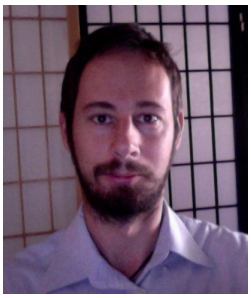

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