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VERY LOW POWER WIRELESS PROTOCOL PERFORMANCE

by
Joshua L. Jabs

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Joshua L. Jabs

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Very Low Power Wireless Protocol Performance

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Joshua L. Jabs

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Abstract

The IEEE 802.11 standard was established to take advantage of the cost savings and ease of use associated with wireless local area networks (LAN). Unfortunately 802.11 falls short in meeting the low power requirements of many applications not directly associated with typical LAN use (i.e. fixed power devices and commonly recharged units). This shortfall is becoming evident with the explosion of a new market for wireless devices such as sensing units, home networks, and portable personal devices. In 1997 the Charles Stark Draper Laboratory began preliminary research into a United States Navy program named Reduced Ships-Crew by Virtual Presence (RSVP). This program calls for numerous battery-powered sensors to wirelessly communicate with a ship's wired backbone. These sensors are considered very low power since they must operate reliably for a period of 10 years without battery replacement. This thesis compares the performance of IEEE 802.11 against a Draper proprietary protocol in an environment characterized by low noise and slow-fat Rayleigh fading.

It will be shown that for standard 802.11 devices, configured optimally for the RSVP environment and neglecting sensory power, the best estimate for lifespan when operating on 3 standard AA batteries is only 36 days. Whereas a device using the RSVP protocol can theoretically operate up to 15 years, much longer than the expected life of a standard battery.

This problem will further be broken down into individual segments of power consumption, to include transmission, reception, and sleep mode. Unlike previous research that has dealt with the physical layer or medium access layer only, this thesis will bring together all aspects of the system to pinpoint the greatest factors in power consumption. It will be shown that the modulation technique and receiving modes of each protocol are irrelevant in the overall life expectancy of the device and that true power savings come in the form of efficient device design and minimizing the protocol requirements required during sleep mode.

The thesis concludes with recommendations given to the RSVP program concerning recent developments in IEEE 802.11 standard devices and the formation of the IEEE 802.15 Wireless Personal Area Network Working Group. The recommendation concludes that a second market analysis should be conducted in respect to the RSVP program.

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Joshua L. Jabs

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Joshua L. Jabs — April 27th, 2000

Joshua L. Jabs — April 27, 2000

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LIST OF ABBREVIATIONS

AP	Access Point
APCM	Access Point Controller Module
BER	Bit Error Rate
BSS	Basic Service Set
BPSK	Binary Phase Shift Keying
CFP	Contention Free Period
CFPR	Contention Free Period Repetition Rate
CP	Contention Period
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCF	Distributed Coordination Function
DSSS	Direct Sequence Spread Spectrum
FHSS	Frequency Hopping Spread Spectrum
IFS	Inter-Frame Space
IR	Infrared
LAN	Local Area Network
MAC	Medium Access Control Layer
MAH	Milli-Amp Hours
MPDU	MAC Protocol Data Unit
NAV	Network Allocation Vector
PCF	Point Coordination Function
PDU	Protocol Data Unit
PHY	Physical Layer
PN	Psudeo-Random
PLCP	Physical Layer Convergence Procedure
PPDU	PHY Protocol Data Unit
PSK	Phase Shift Keying
RSVP	Reduced Ships-Crew by Virtual Presence
SC	Sensor Cluster
TDM	Time Division Multiplexing
WLAN	Wireless Local Area Network

Very Low Power Wireless Protocol Performance

CHAPTER 1

INTRODUCTION

Wireless systems provide two main advantages over their wired counterparts: mobility and reduced installation cost. With research increasing the bandwidth efficiency and technology's ability to meet new consumer demand for both wireless telephony and data communication services, the applications offered to meet these demands have skyrocketed. To meet these new demands the IEEE standards committee released the 802.11 standard for wireless LANs in 1997. IEEE 802.11 covers the Medium Access Control and Physical Layers for wireless LAN communication. This protocol is satisfactory in applications where mobile or portable sensors have access to either fixed power sources or sources that can be recharged or replaced on a regular basis. Unfortunately, the only power saving tool implemented in an 802.11 system is the ability to enter a sleep mode when not transmitting. In applications centered on low power consumption the processing, medium management and transmission requirements of 802.11 fall short.

During the summer of 1998 the Charles Stark Draper Laboratory began work on a United States Navy program labeled *Reduced Ships-Crew by Virtual Presence (RSVP).* This program consists of an infrastructure network with multiple mobile and fixed sensors, where battery life is at a premium with sensors going up to ten years without replacement. This thesis will compare the performance of IEEE 802.11 against a protocol developed specifically for the wireless portions of the RSVP program, henceforth referred to as the RSVP protocol. In addition it will outline areas where 802.11 falls short in meeting the needs of low power systems.

RSVP OVERVIEW

Reduced Ships-Crew by Virtual Presence (RSVP) is a United States Navy sensor program intended to reduce the manpower hours associated with vessel maintenance. The system consists of both fixed and mobile sensors and is required to meet the definition of low maintenance. In the case of RSVP low maintenance implies that sensors will not be replaced while at sea and that battery replacement will only occur once every ten years.

Two key concepts found in RSVP are "reliability" and "survivability". Reliability is defined as the ability to provide accurate data in a timely fashion and will be accomplished by installing redundant sensors. Survivability implies that sensors will continue to provide the system with accurate information in the presence of compartmental damage or system intrusion [5]. This will be accomplished via sensor redundancy, encryption, and efficient protocol selection.

The Draper Labs proposed RSVP architecture is shown below [5].

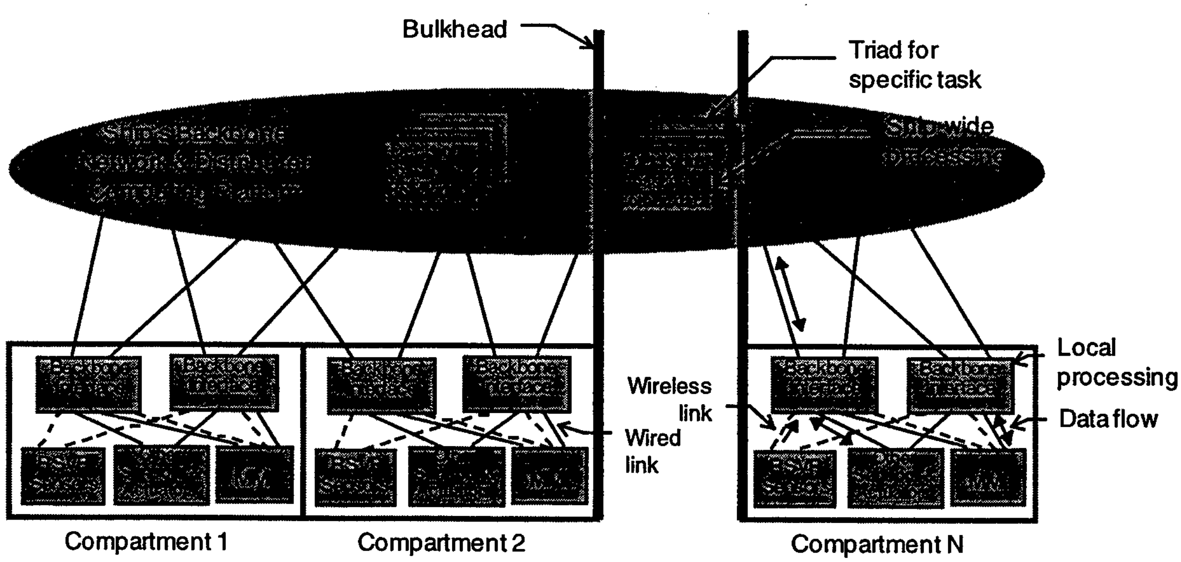


Figure 1. RSVP Architecture

Power consumption is a concern only in respect to the wireless sensor portions of RSVP, since backbone interfaces and data fusion will occur in systems that have access to ship's power. Mobile sensors will be operating on an Aloha channel separate from the individual sensors and will not be examined in this thesis. The equation below generalizes the main factors influencing power expenditure.

$$TotalPower = S + P_s + P_p + TR \qquad (1)$$

where
S = Power used in environmental sensing
P_s=Power used in processing environmental data
P_p=Power used in protocol processing
TR=Transceiver power used in sending and receiving data

Since S and P_s are independent of the protocol chosen, this thesis will only look at P_p and TR. Key RSVP requirements, which impact power consumption, are listed in the table below.

Table 1. RSVP Key Requirements

Requirement Description	Threshold
Time between uplinks	15 min. average 1s minimum capability during loaded condition (min. not average)
Time between downlinks	100s maximum
Maximum environmental raw data size	30 Bytes
Minimum Sensors per Access Point	90 sensors
Maximum BER	10E-5
Battery Power Available	4.5v @ 2850 MAH over 10 years

CHAPTER 2

THEORY

In this section the RSVP and IEEE 802.11 protocols will be explained and methods for comparing them will be presented. Since 1996 a considerable amount of information has been published on the IEEE 802.11 standard, so that only information vital to the content of this thesis will be presented.

METHODOLOGY

To present system power requirements we will start with equation 1 stated previously and again below.

$$TotalPower = S + P_s + P_p + T\mathrm{R} \qquad \text{(1 repeat)}$$

where
S = Power used in environmental sensing
P_s=Power used in processing environmental data
P_p=Power used in protocol processing
TR=Transceiver power used in sending and receiving data

In order to determine the amount of power the receiver and transmitter (referred to above as the transceiver) require, we first need to look at the noise environment in which they are operating and the gain associated with their corresponding modulation schemes. The next step is to determine how often and for what period of time the transceiver needs to be on in order to send/receive data and monitor the medium. This length of time will be determined by the packet size and synchronization requirements of the protocol. Breaking up the equation above for transmission/reception we get the following.

$$TotalPower = S + P_s + P_p + (R + T) \qquad (2)$$

where
R = Power used in reception
T = Power used in transmission

Using the equation above the transmission power is further defined by the generalized equation given below.

(3)

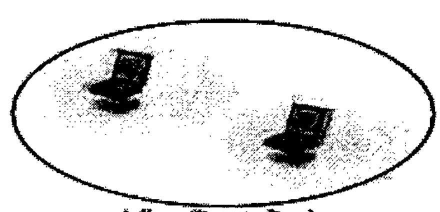
The power required by the processor to manage the protocol and radio is much harder to compute, since much of it is determined in the hardware design. It is expected that a combination of both theoretical and actual data will be required to get an accurate estimate of power consumption.

Estimates for the equipment "on-time" associated with power consumption can be found in a detailed investigation of the Medium Access Control and Physical Layers for each protocol. These will be discussed below.

THE IEEE 802.11 STANDARD

IEEE 802.11 was first conceived in 1990 and ratified as a standard by the Institute of Electrical and Electronic Engineering in 1997[2].

802.11 allows for two different configurations, ad-hoc and infrastructure, which are shown in figure 2. Since RSVP uses access points to connect wireless sensors to the data fusion center, only the infrastructure version of the 802.11 architecture will be explained. The infrastructure architecture uses fixed or mobile wireless sensors to communicate with fixed access points. These fixed access points can be standalone or connected to each other via wired lines. Each access point and its corresponding sensors make up a Basic Service Set (BSS). If mobile sensors exist within the system, the fixed system must be configured to allow for the transfer of these sensors from one access point to the next.



Adhoc (Peer to Peer)

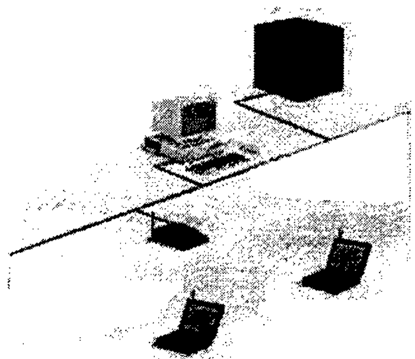


Figure 2. Centrally Controlled Network Vs. Ad-Hoc

PHYSICAL LAYER

As stated above 802.11 places specifications on the standards for both the PHY and MAC layers. 802.11 defines three PHY characteristics for wireless LAN - diffused infrared pulse position (IR), direct sequence spread-spectrum (DSSS), and frequency hop spread-spectrum (FHSS), the latter two networks operate in the 2.4-2.4835 GHz frequency band. Currently cost efficient infrared applications are limited to fixed sensors operating at distances no greater than three feet. Since the RSVP application calls for mobile sensors and operating distances greater than three feet, the infrared physical layer will not be discussed. The other two PHY layers both use spread-spectrum techniques. Spread-spectrum trades off efficient use of bandwidth and power for increased security [1] and decreased random interference. IEEE 802.11 currently allows for both 1Mbit/s and 2Mbit/s transmission rates. Since 2Mbit/s well exceeds the data transmission rate requirements for RSVP only the 1Mbit/s option will be considered.

Spread spectrum systems have increased in number drastically over the past 15 years. In military applications this was primarily due to spread spectrum's ability to resist jamming and evade interception. For commercial uses spread spectrum has increased in popularity mainly because of its resistance to interference. By using a psuedo-random, noise-like signal to modulate the transmitted waveform, spread spectrum transceivers are able to transmit and receive a signal using a much lower spectral power density [3]. Essentially the signals appear as noise to all but other spread spectrum receivers working with the same modulation scheme.

DSSS OVERVIEW

As stated above spread spectrum works by transforming a data sequence to look like random noise. In a DSSS system this sequence is usually generated using a series of flip-flops and a shift register known as a feedback shift register. The initial state and length of the shift register determines the randomness and period of the corresponding sequence. Chosen correctly the configuration above can generate at most a period of 2^m binary symbols, where m is the number of shift registers. Since a run of all zeros would result in the register staying in the zero state, this condition is not allowed and the maximum period of the psuedorandom, PN, sequence is 2^m-1. The significance of this logic is that to maximize the system gain a sequence must appear as random as possible. To do so longer sequences of registers are required or shorter symbol times must be achieved. The symbol time is known as the chip rates. In low power systems this requires more processing power. The 802.11 standard calls for a baseband chip rate of 11 MHz (11 chips per bit) with the chipping period derived below.

$$
\begin{aligned}
N &= 2^m - 1 \\
N &= 2^{11} - 1 \qquad (4) \\
N &= 2047
\end{aligned}
$$

where

N is the period

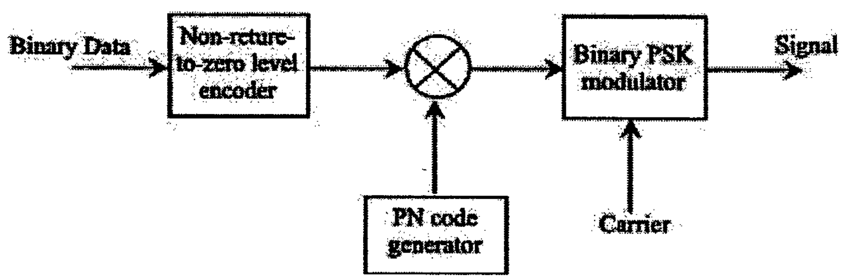
m is the PN chip code.

This chipping rate covers the baseband only. The signal must still be Binary Phase Shift Key, BPSK, modulated into a passband signal suitable for transmission. This modulation is termed the basic Access Rate and is based on 1Mbit/s Differential BPSK, DBPSK using the encoding table below[4].

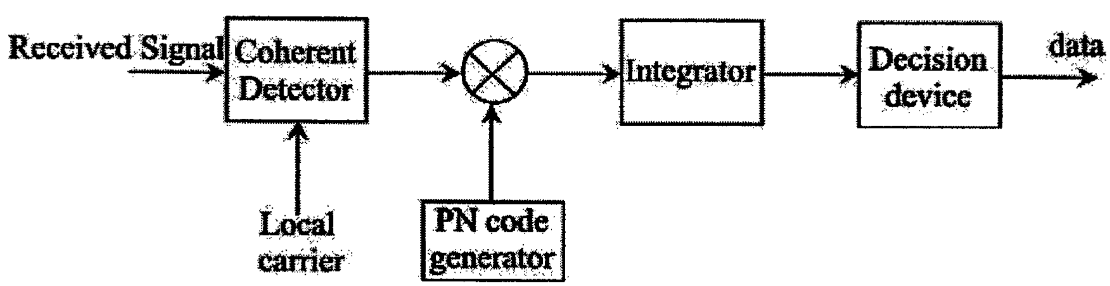
Table 2. 1Mbit/s DBPSK Encoding Table

Bit Input	Phase Change (+jπ)
0	0
1	π

The block diagrams below show physical implementations of both stages of the DSSS/DSBPSK modulation scheme.



(a)



(b)

Figure 3. DSSS Transmitter (a) and Receiver (b)

DSSS/DSPBSK POWER REQUIREMENTS

Two main environmental assumptions are vital to figuring out power consumption requirements in relation to modulation technique. The first is that the channel is "slow." A slow environment is one in which the impulse characterization of the channel changes slowly with response to transmission rate. This is important since it will allow us to use a static environmental variable. The second assumption deals with Doppler effect. Since all sensors discussed in this thesis are stationary we will assume that Doppler effect due to motion does not apply. We will also assume that the presence of moving bodies in the environment is negligible. In doing a quick analysis of actual environmental data (to be presented later) it seems reasonable to consider a Gaussian noise distribution and that the MAC layer completely eliminates multi-user interference. Taking into account the later, the following probability of error derivation will start with the assumption that there are k users transmitting. The signal transmitted by user, k, is shown below [7].

$$S_k(t) = \sqrt{\frac{2E_s}{T_s}} m_k(t) p_k(t) \cos(2\pi f_c t + \phi_k) \qquad (5)$$

where $p_k(t)$ is the PN sequence and $m_k(t)$ is the data sequence

Since there can be at most k signals received at the receiver, the receiver must use k transmitter signature sequences to receive a decision variable. This decision variable will relate the numerous received chips to the actual received bit. The received bit for the i^{th} transmitted bit of user 1 is.

$$Z_i^{(1)} = \int_{(i-1)T+\tau_1}^{iT+\tau_1} r(t) p_1(t-\tau_1) \cos(2\pi f_c (t-\tau_1) + \phi_1) dt \qquad (6)$$

Since symbols are received as either +1 or –1 and then converted to a corresponding binary 1 or 0, if $m_{l,I}$=-1 (m is the symbol received), then there will be an error if $Z_1^{(1)}$=1. So the probability of error can be calculated as

$$\Pr[Z_i^{(1)} > 0 \mid m_{l,i} = -1] \tag{7}$$

which simply restates the proceeding paragraph. Since the received signal r(t) is a linear combination of all signals received (6) can be rewritten with the following two equations.

$$Z_i^{(1)} = I_1 + \sum_{k=2}^{K} I_k + \xi \tag{8}$$

where I_1 is the desired signal, I_k are all the other signals, and ξ is the noise and I_1 is described below.

$$I_1 = \int_0^T S_1 p_1(t)\cos(2\pi f_c t)dt = \sqrt{\frac{E_s T}{2}} \tag{9}$$

Since a Gaussian noise distribution was assumed the noise variable ξ becomes

$$\xi = \int_0^T n(t) p_1(t)\cos(2\pi f_c t)dt \tag{10}$$

As stated above I_k is composed of the cumulative effects of all transmitting stations. The central limit theorem then implies that the sum of the effects would tend toward a Gaussian distribution [7]. This yields a convenient expression for the average probability of bit error

$$P_{be} = Q\left(\frac{1}{\sqrt{\frac{K-1}{3N} + \frac{N_0}{2E_b}}}\right) \tag{11}$$

As stated earlier both protocols use a medium access control that will only allow a single transmitter to utilize the medium at any given time. This reduces the above equation to that of BPSK given below.

$$P_{be} = Q\left(\sqrt{\frac{N_0}{2E_b}}\right) \tag{12}$$

The equation above neglects the impact of multipath interference. In many slow, fat fading indoor environments the path gain associated with multipath can be expected to follow a Rayleigh distribution [7]. This will be shown to be true for RSVP later in this thesis. To evaluate the probability of error in this type of environment the average probability of error for a specific modulation scheme must be averaged over the average signal strength due to fading. A general equation for this calculation is given below.

$$P_e = \int_0^\infty P_e(X)p(X)dX \tag{13}$$

where $P_e(X)$ is due to the specific modulation scheme
X is the signal to noise ratio
where $X=\alpha E_b/N_0$
α is the amplitude of the fade
and
p(X) is the pdf of X due to fading

For Rayleigh fading channels:

$$P(X) = \frac{1}{\Gamma}\exp\left(-\frac{X}{\Gamma}\right) \tag{14}$$

where $\Gamma=\alpha^2 E_b/N_0$

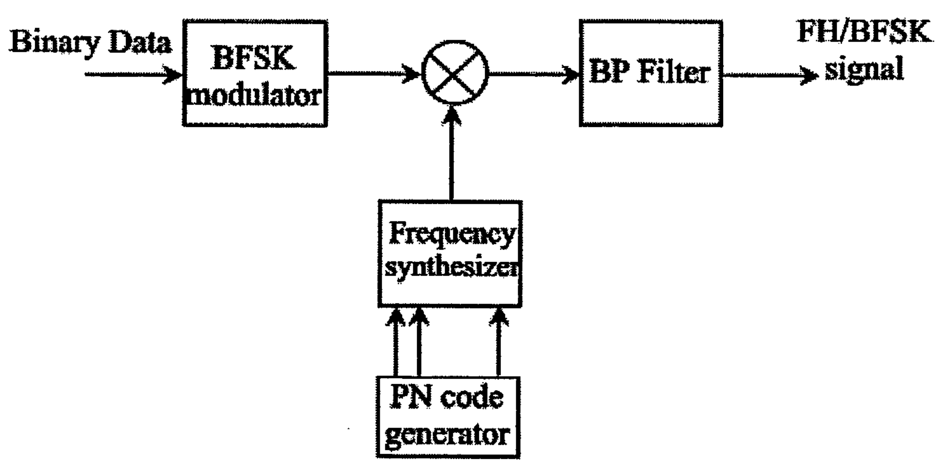
Substituting (14) and (12) into (13), the probability of error for coherent BPSK is given below

$$P_e = \frac{1}{2}\left[1 - \sqrt{\frac{\Gamma}{1+\Gamma}}\right] \qquad (15)$$

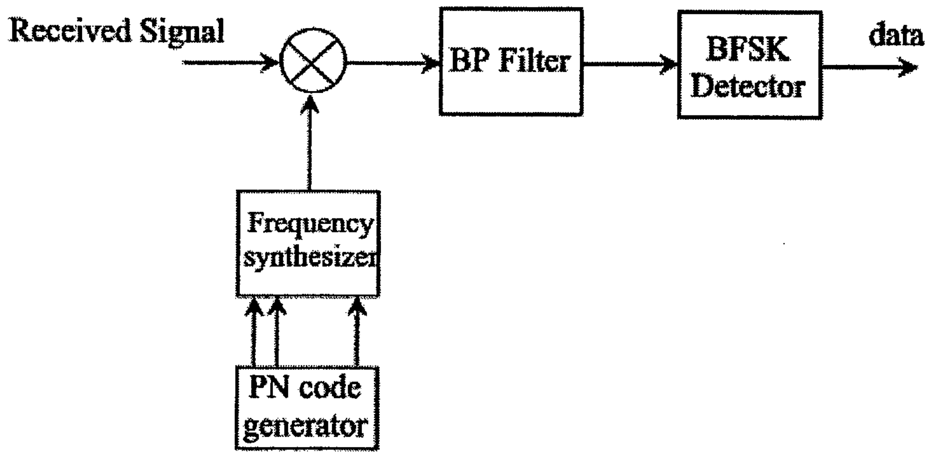
This equation will be used to find the minimum required power to transmit through the RSVP channel.

FHSS OVERVIEW

As with DSSS, FHSS works on the principle of spreading a narrowband signal over a large bandwidth. FHSS achieves this spreading by forcing its transceiver to hop from frequency to frequency based on the results of a PN code. Two main types of FHSS exist. The first processes one to several bits of data during a single hop and is referred to as slow-FHSS. The second type of FHSS is fast-FHSS and switches frequencies multiple times during each bit transmission. In AWGN both have the same performance. The main advantage of fast-FHSS involves its ability to evade jammer detection and transmission by moving to a new frequency before the jammer can cause any interference.



(a)



(b)

Figure 4. FHSS Transmitter (a) and Receiver (b)

For 1 Mbit/s, IEEE 802.11 defines binary frequency shift keying modulation (M=2) and has specific lists of available hopping patterns. Since AWGN is assumed these hopping patterns and rates are not relevant to this thesis, though slow hopping is assumed.

FHSS POWER REQUIREMENTS

If the only interference is in the form of AWGN and we assume the same slow fading channel as stated in the description of DSSS above the derivation for probability of error used in [7] becomes relevant as shown below.

$$r(t) = \alpha(t)\exp(-j\theta(t))s(t) + n(t) \qquad 0 \le t \le T \qquad (16)$$

where
r(t) is the received signal
α(t) is the channel gain
θ(t) is the phase shift
and
n(t) is AWGN

As was done in the DSSS probability of error derivation, the average probability of error will be taken across the channel over the possible ranges of signal strength due to fading.

This is accomplished by averaging the error in the AWGN over the fading probability density function. Since perfect medium control is assumed the performance of FHSS can be characterized using the equation for noncoherent FSK. The FSK probability of error is given below:

$$P_e = \frac{1}{2}\exp\left(-\frac{E_b}{2N_0}\right) \tag{17}$$

Substituting this equation into (13) given above reduces the probability of error for FHSS/BFSK in AWGN with a Rayleigh fading channel to:

$$P_e = \frac{1}{2 + \frac{E_b}{N_0}\overline{\alpha}^2} \tag{18}$$

Rearranging to solve for bit energy we will be able to solve for the power required to transmit through the medium.

802.11 MEDIUM ACCESS LAYER

The MAC layer is independent of the type of PHY layer being used in the individual 802.11 system and is very similar to the IEEE 802.3 Ethernet specification. 802.11 MAC specifies an asynchronous, contention free access method. This is accomplished using one of two type of configuration. The Distributed Coordination Function (DCF) allows for many transmitting stations to operate within the same signal space as in an ad-hoc setup. The second configuration is know as the Point Coordination Function (PCF) and is utilized in an infrastructure setup where one transmitting station, known as an Access Point (AP), controls the medium. When operating both a PCF and DCF the medium is divided into two periods known as the contention free period (CFP) and the contention period (CP). During the CFP the point coordinator, henceforth referred to as the Access Point (AP), controls the medium through polling, where as during the CP a carrier sense multiple access with collision avoidance (CSMA/CA) scheme is used to control the medium. The PCF scheme is most appropriate for meeting the critical requirements of RSVP but both will be utilized in order to allow for larger uploads from the SC and future growth (figure 5). To understand the setup required and the processing required, both schemes must be explained.

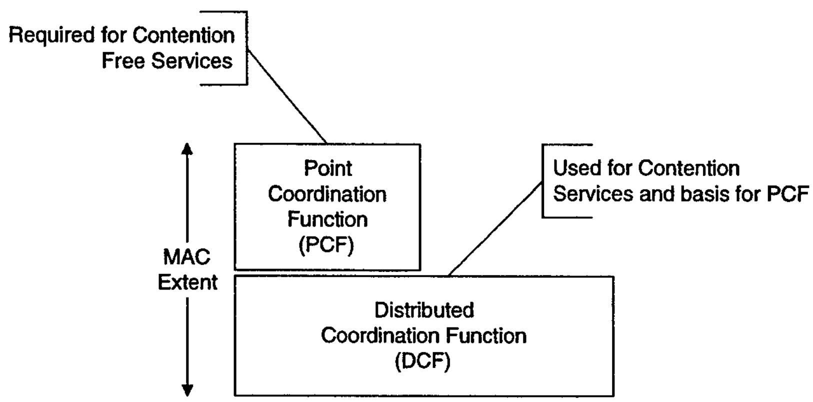


Figure 5. MAC Architecture

Distributed Coordination Function (DCF). The DCF is the underlying MAC function employed by 802.11. It uses a medium management function know as carrier sense multiple access with collision avoidance (CSMA/CA). In order to transmit a station must sense the medium for a specified amount of time. If sensed busy the station listens for the transmission's end, waits a random amount of time, and tries again. One variation to this can be implemented to reduce the chances of hidden terminal problems. Instead of immediately transmitting an entire message, the station first sends a much shorter request to send (RTS) frame, which specifies data frame length. If enough time remains the AP will acknowledge the transmitting station with a clear to send (CTS) at which time the station will transmit its full message. Since the SC in RSVP will only use this method for a small number of transmissions, no more will be discussed on RTS/CTS method and it will be left out of power calculations.

Inter-Frame Space (IFS). The PCF is built on top of the DCF. To do so 802.11 makes use of the Inter-Frame Space (IFS). The IFS is defined as the time interval between frames. Four different IFS are available and their length determines channel priority, as modules operating with shorter wait times will always be able to access the medium first. The table below lists the IFS with the top being the shortest to bottom being the longest.

Table3. Inter-frame definitions

SIFS	Short Inter-frame Space
PIFS	PCF Inter-frame Space
DIFS	DCF Inter-frame Space
EIFS	Extended Inter-frame Space

The diagram below shows how waiting with a shorter IFS allows prioritized access to the medium[4].

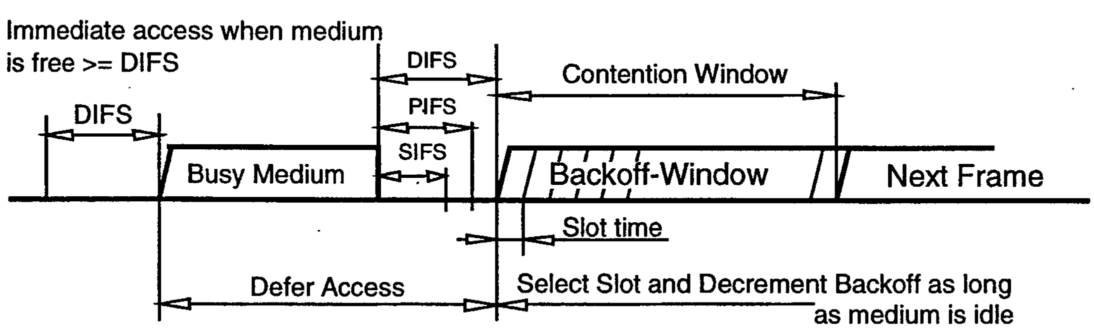


Figure 6. Inter-frame Spacing

The SIFS is used by the PCF to poll transmitting stations, henceforth referred to as sensor clusters (SC), during the CFP. The polling scheme will be explained later. SC use the PIFS to request polling during the CFP and the DIFS to gain access to the medium during the CP. The EIFS is used in the case where a collision has been detected, but is not of concern for this thesis.

Network Allocation Vector (NAV). IEEE 802.11 conserves power through the use of a Network Allocation Vector (NAV). Instead of sensing the medium at the start of every frame a SC uses the NAV as a form of virtual carrier sensing. By listening to the data either sent by the AP or by transmitting stations a SC can determine how long the medium will be in use. This time period is the Network Allocation Vector (NAV). A SC will set its NAV and not try to transmit until it has been decremented to zero.

Point Coordination Function (PCF). The primary responsibility of the PCF is to provide contention free medium access. A SC is said to be CF-pollable if it can be polled by the PCF. All SC in RSVP are pollable. When polled by the AP a SC may send one data frame and if necessary an acknowledgement from an earlier frame. If transmission fails the SC may not retransmit unless polled again or until the CP begins. A system using a CFP will still have a CP. These shall rotate on a periodic basis set by the controlling AP. The rate at which the CFP cycles is known as the Contention-Free Repetition Rate (CFPRate). An important characteristic of the standard is that a message started during the CFP will be allowed to spillover into the CP. To guarantee service to all SC during each CFP, the length of the CFP must be set to allow for worst-case spillover. To control the medium the AP will gain access using the shorter PIFS. It will then send a beacon containing the CFP setup information known as the CF Parameter Set Element. Available CFP transmission types from the AP are:

- Data, Data+Poll (data to SC and poll another), Data+Ack, Data+Poll+Ack (data to SC, ack last SC, and Poll next), Poll, Ack+Poll, Ack, CPEND

Available CFP SC transmissions include:

- Data, Data+Ack, Ack

The AP is responsible for handling the order and arrangement of frames transmitted during the CFP.

802.11 MAC Frame Formats. As stated above there are a number of different frames available for MAC transmission. We will now analyze these different frame types and select those required for use by RSVP. Each of these frames consist of the following three basic elements [2] .

1) A *MAC Header*, which comprises frame control, duration, address and sequence control information.

2) A variable length *Frame Body*, which contains information specific to the frame type.

3) A *Frame Check Sequence* (FCS) which contains an IEEE 32-bit CRC

These elements are composed into a general frame format. This frame format is comprised of elements that always occur in the same order. The following figure demonstrates the general MAC frame format, with the numbers above representing the number of bytes included in each block. The only exceptions to this rule are in the Address 2, Address 3, Sequence Control, Address 4, and Frame Body, which are only present in certain frame types. This will be discussed more later.

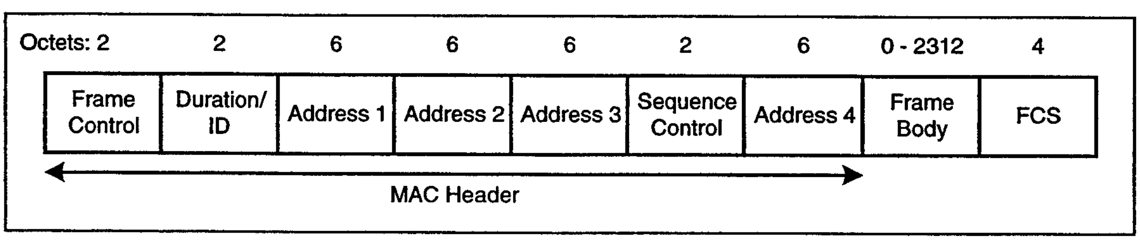


Figure 7. General Frame Format

The exact contents of each field are not relevant to this thesis. What is important is that these fields are transmitted with every frame and thus take power in management and transmission. This will be taken into account when calculating frame duration. For a complete description of MAC frames see [4]. The frames that are of interest to this thesis are, in respect to transmission, SC data frames, and in respect to reception, AP poll frames, AP Beacon Frames, and AP acknowledgement frames. These are categorized into control frames, data frames, and management frames by 802.11 and are described below.

Control Frame. Each control frame has the following frame control block.

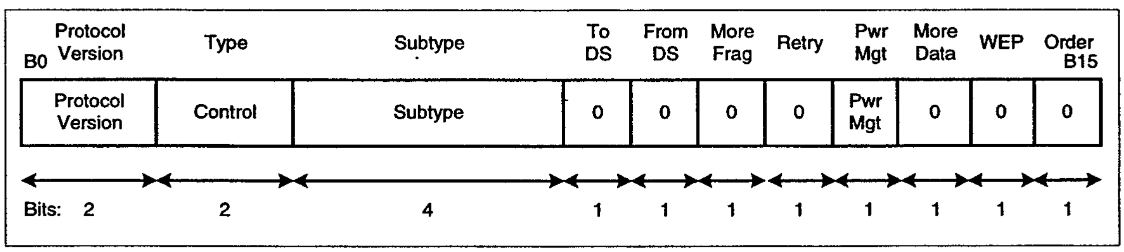


Figure 8. Frame Control Field and Subfield Values Within Control Frame

An acknowledgement frame is a type of control frame and has the following format.

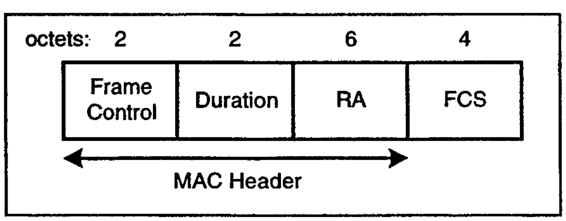


Figure 9. ACK Frame

The Receiver Address (RA) portion is in respect to who is being acknowledged. What is important to note about this frame is its 14-byte length.

Another control frame of interest is the PS-Poll frame. This is a polling frame used by the AP and is 20-bytes in length. Its format is shown below.

octets:	2	2	6	6	4
	Frame Control	SID	BSS ID	TA	FCS

MAC Header

Figure 10. PS-Poll Frame

The CF-END is send by the AP to signify the beginning of the CP. Each frame is 20-Bytes in length and is shown below.

octets:	2	2	6	6	4
	Frame Control	Duration	RA	BSSID	FCS

MAC Header

Figure 11. CF-END Frame

Data Frames. Each data frame has the following generalized format, regardless of the number of addressees.

Octets: 2	2	6	6	6	2	6	0 - 2312	4
Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Frame Body	FCS

MAC Header

Figure 12. Data Frame General Format

Address 4 will be omitted in the case of RSVP. It is reserved for AP to AP transmissions and when not used is physically omitted. For the purposed of RSVP the Frame Body will contain a 30 Byte message. This is defined as the average message length sent both to and from SCs. Taking this into account the MAC data frames become 58-Bytes in length.

Management Frames. The generalized format for the management frame is described below.

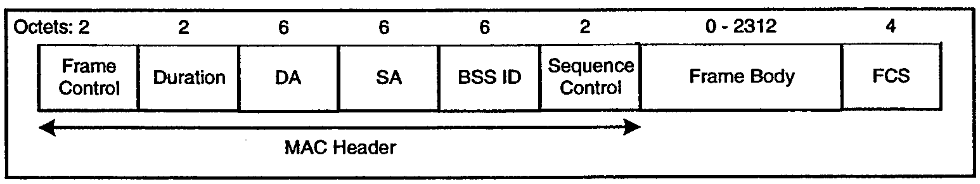


Figure 13. Generalized Management Frame Format

A relevant management frame is the AP beacon frame. The beacon frame's frame body is shown below.

Table 4. Beacon Frame, Frame Body

ORDER	INFORMATION	NOTE
1	Timestamp	
2	Beacon Interval	
3	Capability Information	
4	SSID	
5	Supported Rates	
6	FH Parameter Set	1
7	DS Parameter Set	2
8	CF Parameter Set	3
9	IBSS Parameter Set	4
10	TIM	5

It is important to note the following. For RSVP either the FH parameter will be used or the DS parameter, but not both, depending on whether DSSS or FHSS is implemented. TIM is present whenever a beacon is directed by an AP, which is true for RSVP. IBSS will not be present for the purposes of this thesis, since it a parameter implemented for IBSS. Only their lengths are of direct importance and are given in the table below.

Table 5. Frame Body Length

INFORMATION	LENGTH
Timestamp	1 Byte
Beacon Interval	2 Bytes
Capability Information	2 Bytes
SSID	32 Bytes
Supported Rates	4 Bytes
FH/DS Parameter Set	7 Bytes/3 Bytes
CF Parameter Set	8 Bytes
TIM	6 Bytes

The last block of TIM consists of a virtual bitmap with a variable length of 1-251. This is a reference for the number of buffered frames addressed to a certain SC. For RSVP the assumption is made that relatively little downstream traffic is expected and so the length of this element should not exceed 1 byte. This would make the TIM 6-bytes in length, the Frame Body is equal to 62 Bytes for a FHSS frame and 58 Bytes for DSSS, and the average length of a AP beacon frame equal to 92 Bytes.

802.11 MAC/PHY CONVERGENCE

The convergence of the MAC/PHY layers essentially consists of getting data ready for transmission and is unique to the PHY being implemented. DSSS will be covered first, followed by FHSS.

DSSS Convergence. Data packets, such as the data frames described above, are technically referred to as Protocol Data Units (PDUs). Those originating in the MAC are labeled MAC Protocol Data Unit (MAC PDU). Convergence is the process of moving the MPDUs into PHY Protocol Data Units (PPDU), essentially getting the data into a format suitable for transmission. The diagram below shows how the MPDU is packetized into a PPDU.

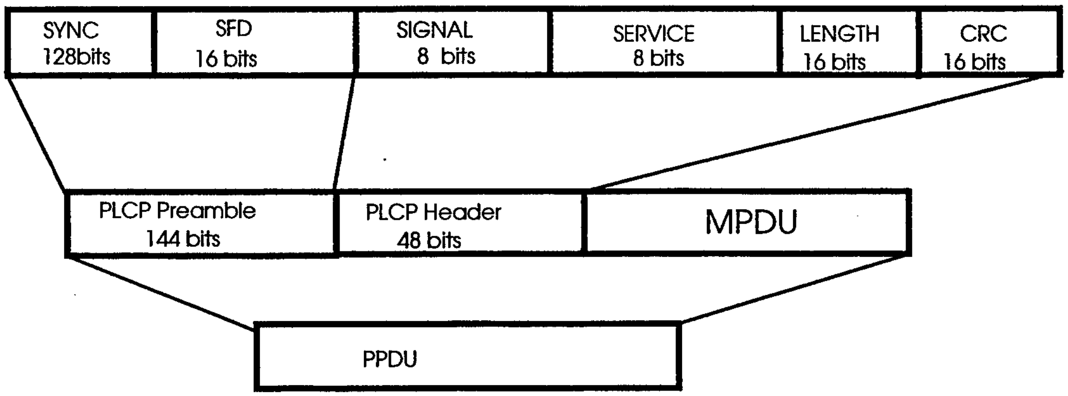


Figure 14. DSSS MPDU to PPDU Packetization Format

Definitions for the abbreviations used in figure 14 are given below.

PLCP:	Physical Layer Convergence Procedure
Sync:	Synchronization
SFD:	Start Frame Delimiter

The specific value of these fields and their meaning is not important. It is important to note the length of these fields, as they will be used in power calculations. In understanding DSSS processing power it is important to note that the entire PLCP packet will be scrambled using the following polynomial.

$$G(z) = z^{-7} + z^{-4} + 1 \qquad (17)$$

Once the data is scrambled it is sent to the PHY layer for transmission where it follows the modulation scheme described above in DSSS PHY.

FHSS Convergence. THE FHSS MPDU to PPDU convergence process is similar to that stated for DSSS. The PLCP frame format is shown below.

PLCP Preamble		PLCP Header			PLCP_PDU
Sync	Start Frame Delimiter	PLW	PSF	Header Error Check	
80 bits	16 bits	12 bits	4 bits	16 bits	Variable number of octets

Figure 15. FHSS MPDU to PPDU packetization format

Definitions for the abbreviations used in figure 14 are given below.

Sync: Synchronization
PLW: PLCP_PDU Length Word
PSF: PLCP Signaling Field

Once again the exact contents of these fields are not important, just the fact that they are transmitted each time and contain a static number of bits. The main difference between the MPDU in DSSS and the PLCP_PDU in FHSS, comes from an added step. In FHSS the MPDU undergoes data whitening. Where DSSS uses a PN sequence to generate random data before transmission, the PLCP for FHSS PHY uses a 127 frame-sequence scrambler followed by 32/33 Bias-Suppression Encoding to randomize the data and run lengths [2]. The generating polynomial is given below.

$$S(x) = x^7 + x^4 + 1 \qquad (18)$$

This method results in the following PLCP frame format.

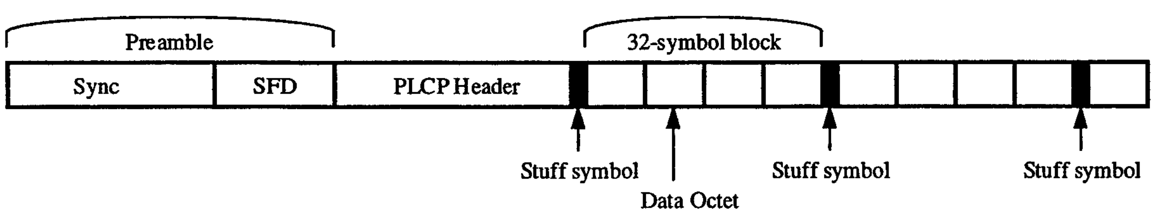


Figure 16. PLCP Frame Format with Associated Whitening

This data is sent to the PHY transmission entity to be put onto the medium as described in the FHSS PHY section above.

Note. It is important to note that I have omitted any discussion of the Physical Medium Dependent Sublayer for both DSSS and FHSS. This sublayer deals with sending primitives that setup the PHY layer entities for transmission and reception. There are two main reasons for this omission. Configuration in RSVP is expected to be very static, in that there is no peer-to-peer traffic, switching of modulation rates, etc. For this reason most of the information required to be sent to and from the PMD sublayer will not change. The second reason for omission stems from the inability to put a power consumption estimate on this data. This data flows continuously in the system and is characterized by the sleep mode power consumption of the IEEE 802.11 equipment. An estimate based on current equipment will be factored in during final power calculations.

RSVP PROTOCOL OVERVIEW

The RSVP MAC/PHY protocol was written specifically for the RSVP program. Sensors are intended to operate in conjunction with specific radio architectures and by doing so, the protocol has eliminated the need for a true MAC/PHY convergence sublayer. Instead this information is provided in MAC definition. I have outlined the RSVP MAC following the 802.11 format in order to simplify its understanding. The system will follow the infrastructure scheme of 802.11, with Access Points controlling all communication. Two key differences between 802.11and RSVP are that sensors in RSVP can communicate only with the access points and work through a slotted Time Division Multiplexing (TDM) scheme instead of AP polling.

The RSVP protocol is designed with emphasis on the following four main requirements: Low power, high reliability, adaptability under loaded conditions, and no preference to sensor data or sensor requests based on location. Since RSVP is a specific application protocol and not a common standard it will be described in more detail than IEEE 802.11.

RSVP PHYSICAL LAYER

RSVP uses noncoherent FSK modulation to transmit wireless data over the physical medium in the 2.4GHz range. Frequency shift keying was defined above in the FHSS discussion. RSVP uses a "smart" MAC to select frequencies. This psuedo-frequency diversity scheme works as follows. An AP will initially be powered on with a frequency assigned by a base station on the wired network. If its current frequency is not sufficiently strong enough to meet the probability of error requirements for each of its SC it will move to another available frequency or tell the SC to find another AP. For this to work the transmission power must be high enough to permit transmission by a minimum of 100 sensors (as per RSVP requirements) within each APs assigned spectrum. The RSVP receiver requires 17dB of SNR to properly receive the signal [10].

RSVP MEDIUM ACCESS LAYER

The RSVP MAC layer is designed around an RF channel operating minimally at 200Kbps. The protocol Time Division Multiplexes (TDM) each Access Point (AP) channel (single frequency) into 111 slots, thus requiring synchronization between transmitter and receiver. These 111 slots together make up one APCM/SC (Access Point Controller Module/Sensor Cluster) cycle. The last slot is unused due to the inability of the SC radio to transmit and switch its radio over in time to receive the AP transmission. This allows for a maximum of 99 SCs per AP. The APCM/SC cycle is divided as shown in figure 16.

H	B	F_0	F_1 •••	F_{99}	U

Figure 17. APCM/SC Cycle Division

H: Access Point Sync Frame (slot 0)
B: Bandwidth on Demand Block (slots 1-10)
F: Normal Sensor Frame (slots 11-110)
U: Unused

A typical cycle begins with the AP's transmission of an H frame. This frame is used for AP to SC data transmission and SC synchronization. This is the only time in which data can be transmitted to the SCs. Immediately following the H frame is a multipurpose ten-frame Bandwidth on Demand block (B). This block is used both by the AP and SCs for larger data transmissions and must be negotiated. When unused for large transmissions this block is utilized by new SCs to request channel access. By listening to the H frame a new SC will be able to determine B frame availability. When granted access to an AP, the SC will be designated a slot number (11-110). During this slot the SC will transmit any ready data to the AP. If no data is present the slot will remain empty.

Slot Assignment Methodology. The AP assigns slots to the SCs during the SC's initial configuration process. Each AP is capable of supporting up to 99 SCs. To conserve power initial slot assignments will be given out by spacing them one slot apart (i.e. 1, 3, 5). This will allow the SCs to take advantage of a more lenient synchronization scheme, staying idle longer and saving power. In addition, the AP will turn away new requests after reaching a capacity of 50 SCs. SCs that cannot find another AP will still be able to establish a connection using an emergency request to the AP, forcing the AP above 50 SC and into the more stringent synchronization mode.

SC Listening Offset. Each SC must power on its radio a minimum of once every 100s (lenient sync) to synchronize its radio. SC will accomplish synchronization by listening to the first 18 Bytes of the H frame header. This is the only time the AP can transfer information to the SC. In order to ensure maximum use of this time the SC will be assigned a specific synchronization time based on the overall AP time (AP time is a continuous repeating sequence broadcast in the H frame, which runs from 11-110). If a SC is assigned slot 45 then it will wake up during every AP time 45. If the system increases the synchronization rate, say to 50s, the SC will synchronize every 50s, but only listen for an AP downlink every 100s. The following simplified diagram depicts this system for three SCs and does not include the BOD slot.

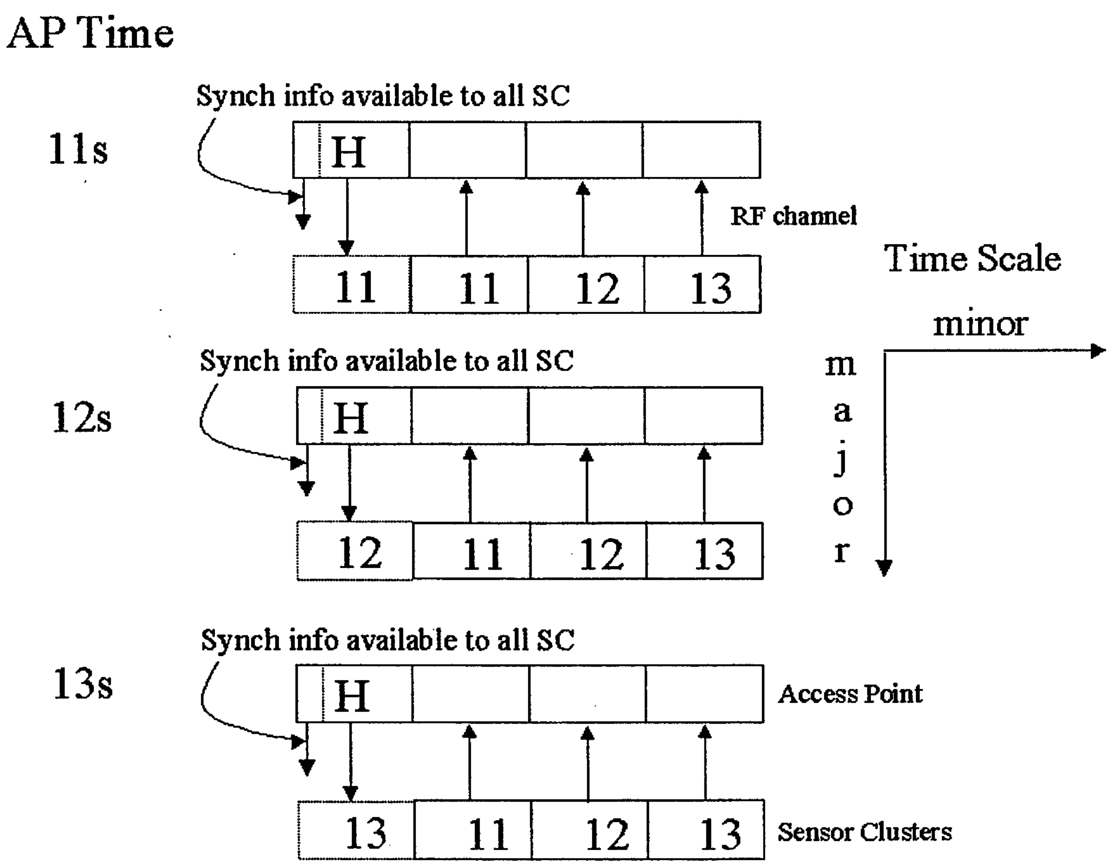


Figure 18. AP Time and SC offset

A side benefit to the SC offset occurs in the event of an AP failure. Since the SC synchronization times are skewed by a minimum of one second, each SC will discover the AP failure one second apart and move to find a new AP in one second intervals, giving available APs a minimum of one second to grant new access.

Slotted Performance. The following table depicts the performance characteristics of the APCM/SC slotted protocol.

Table 6. APCM/SC Protocol Performance Characteristics

Gross Data Rate	200Kbps
Sensor Transmit Period	Up to 1s
Frame Size	512b Gross 240b Effective
Sensors Per Axis Point	99 max

APCM/SC Packet Format. The following describes the packet formats for both APCM to SC communication and SC to APCM communication, as well as the format of the bandwidth on demand block.

APCM to SC Packet Format. The APCM to SC packet is transmitted during the H frame. The H frame can be used by the APCM to grant access to new SCs, kickoff SCs currently on the channel, and to manage the bandwidth on demand (B Block). It is also used by the SCs for synchronization.

Byte #	Bit 7	6	5	4	3	2	1	0	Value (hex)
1	Message Header								
2									
3									
4	Message Type								
5	AP Frequency								
6	AP Frame Time								
7	Flags								
8	AP Frequency Table								
9									
10									
11									
12									
13									
14									
15	Destination ID								
16									
17									
18									
19	Message Information (from AP)								
20	•								
21	•								
22	•								
•									
•									
N									
n+1	CRC-16								
n+2									

Figure 19. APCM to SC Packet Format

SC to APCM Packet Format. There are two types of SC transmissions. The first SC transmission occurs during an F frame. This packet is used by the SC to transmit data to the AP and will be the basis for power analysis. The second type of SC transmission is used to request new access and during the B block. The second type is presented to show protocol use only and will not be factored into total power requirements. Both transmissions follow the format below.

Byte #	Bit 0	1	2	3	4	5	6	7	Value (hex)
1	SC Header								
2									
3									
4	Message Type								
5	ID LSB								
6	Message Information								
•	•								
•	•								
N	•								
n+1	CRC-16								
n+2									

Figure 20. SC to APCM General Packet Format

RSVP PSUEDO-CONVERGENCE

For power calculations it is important to note that besides the CRC used for the RSVP packets, each individual byte includes a start, stop and parity bit. This essentially makes every byte 11 bits instead of 8.

CHAPTER 3

POWER COMPARISON METHOD AND ANALYSIS

This methodology section takes into account that which has been shown in theory and moves it into a format suitable for comparison. Once again the equation below is presented as a reference point.

$$TotalPower = S + P_s + P_p + (R + T) \qquad \text{(2 repeat)}$$

where
S = Power used in environmental sensing
Ps=Power used in processing environmental data
Pp=Power used in protocol processing
R = Power used in reception
T = Power used in transmission

Since the power used in gathering and processing environmental data is protocol independent it will be left as an unknown constant in figuring total consumed power. R will be included with Pp, with our main focus on T. The total transmission power consists of the average time spent transmitting, t_t and the average transmitted power, Pt. t_t is derived from the MAC protocol and RSVP requirements, where as Pt is derived from the modulation scheme specified by PHY. The following equation takes these factors into account in solving for the total length of time a SC using each protocol will operate.

$$\frac{2850mAH * 4.5V * .000114\frac{years}{hour}}{TotalPower1cycle * Cycles\, in\, ayear} = \#ofyears \tag{19}$$

where

$$TotalPower1cycle = (T_t * P_t) + (T_r * P_r) + (T_s * P_s) \tag{20}$$

RSVP specifies that a SC will transmit at an average rate of once every 15min. The length of each of these transmissions is protocol dependent and will be described below.

The first step is to solve for the amount of expected transmission "ontime". For both versions of 802.11 the SC will synchronize or sleep until polled by the AP during the appropriate CFP. The average case will be an AP to SC poll once every 15min. The SC will then transmit the data, wait for an acknowledgement, and go back into sleep mode.

For DSSS SC transmission will consist of sending a 58 Byte data packet rapped in 24 Bytes of PHY overhead, for a total of 82 Bytes. Using the equation below we solve for transmission "ontime".

$$t_t = \frac{\#Bytes}{TransmissionRate} \tag{21}$$

$$t_t = \frac{82Bytes * \frac{8bits}{Byte}}{\frac{1Mbit}{s}}$$

$$t_t = 656\mu s$$

This neglects the time it takes to prepare for transmission and we will assume this to be negligible in respect to total transmission time.

For FHSS SC transmission the equation remains the same but the overhead is reduced to 129 bits.

$$t_t = \frac{58Bytes * \frac{8bits}{Byte} + 129bits}{\frac{1Mbit}{s}} \tag{22}$$

$$t_t = 593\mu s$$

For RSVP the system will be operating with a transmission rate of 200Kbps.

$$t_t = \frac{30Bytes * \frac{8bits}{Byte} + 146bits}{\frac{200Kb}{s}} \tag{23}$$

$$t_t = 1.93ms$$

As discussed in the Theory section, the RSVP channel is characterized by two main factors; noise and fading. We will now attempt to characterize the required parameters based on the equations for probability of error found above and restated below. Data for these examples was taken aboard a U.S. Navy Vessel [9]. We will be using a single sample, assumed to a worse case characteristic of the environment and will assume that the environment is not frequency selective. A typical propagation measurement is shown below. This measurement was taken in one of the main engine rooms, where the amount of machinery increases the multipath effects, thus it is expected that this measurement approaches worst case. The data was plotted using [10].

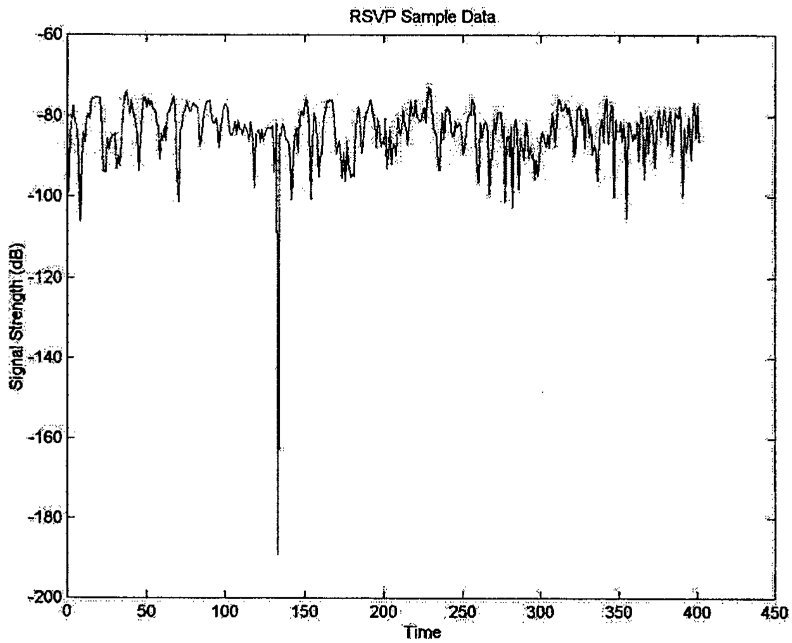


Figure 21. RSVP Environmental Propagation Measurement

By plotting a histogram we can get a visual idea of the expected distribution and verify the Rayleigh assumption. Manipulating this data we can obtain the associated Rayleigh path gain.

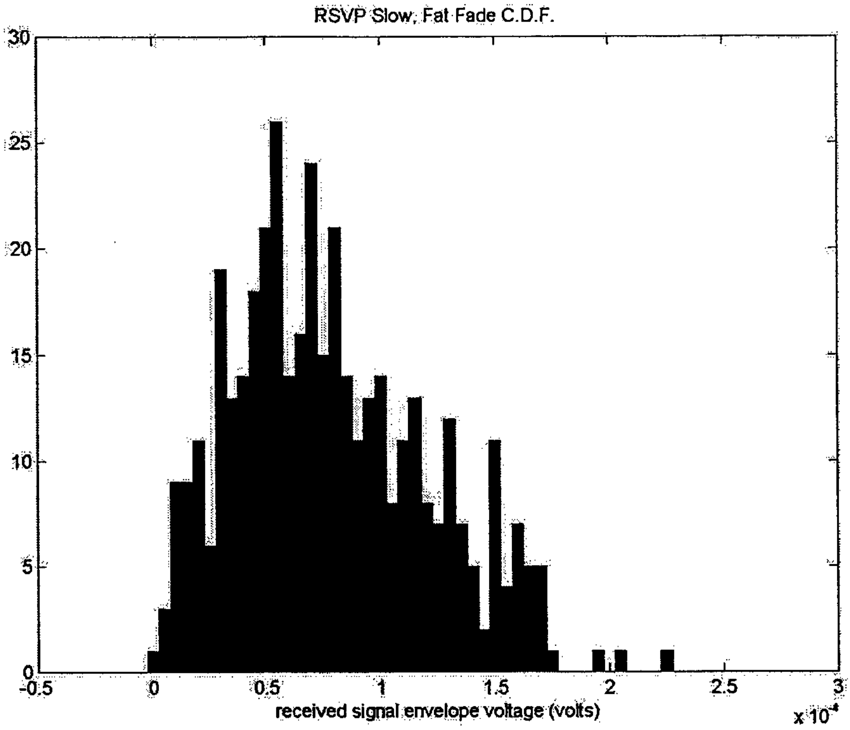


Figure 22. Histogram of Propagation Measurement

The Rayleigh parameter is found from the time average value of the simulation data associated with the figure above and has a value $8.9*10^{-5}$. The other parameter required for calculating required energy is the noise level. At 2.4GHz the noise level is expected to be low, as most interference does not reach frequencies this high. The signal below was derived by transmitting an unmodulated signal through the compartment at a distance of 20 meters.

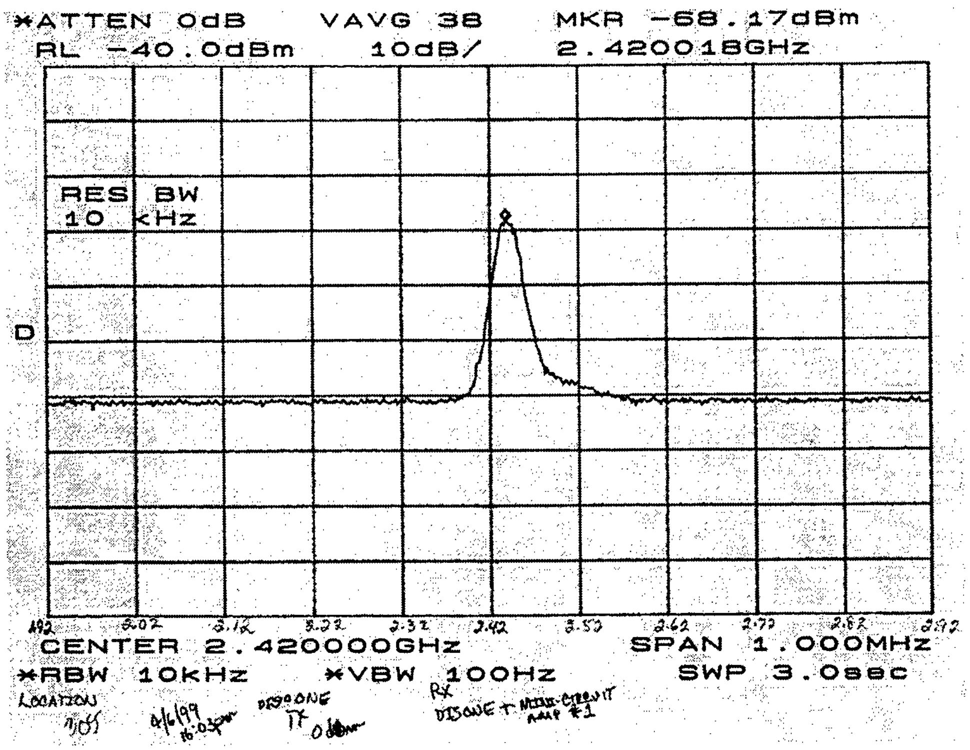


Figure 23. Propagation Measurement

Using this plot as characteristic of the environment we can use the following to equation to adjust for the analyzer bandwidth and the 30 dB preamp to get the actual noise parameter.

$$NdBm = -100 - 30 + 10Log_{10}(200KHz/10KHz)$$

$$NdBm = -117 \tag{24}$$

Using equation 13 and solving for the bit energy we find that the transmission power required to achieve a BER of 10^{-5} for DSSS is 6.3mW per bit and that for FHSS 25.2mW per bit is required.

Using the RSVP protocol's FSK system the calculation of required transmission power is somewhat simplified. Since the AP is allowed to maximize channel usage by changing frequencies based on the RSSI of each of its SC, we may assume that it will select the least faded channel. In doing so the channel can be thought of as line-of-site with no multi-path interference. Taking this into account and leaving 17dB margin for Eb/No the resulting necessary transmission power is 1mW.

Common processing values for transmission, reception, and sleep power, will be extracted from actual equipment as follows in the following table. The assumption is made that stand-bye only occurs briefly before transmission and reception and therefore no value is considered. Only products capable of operating in an infrastructure system are considered.

Table 7. Common SS Characteristics

Manufacturer	Product	Tx	Rx	Sleep	Modulation
Nokia	C020 WLAN CARD	1.7W to tx at 100mW	1.3W	.1W	DSSS
Aironet	PC4800B	2 W to tx at 30mW	1.5W	.05W	DSSS
Instersil	PRISM DSSS PC Card	2W to tx at 56mW	1.5W	NA	DSSS
Symbol	Spectrum24 WLAN	2W to tx at 100mW	1.5W	.015W	FHSS
Intermec Technologies	2125 OpenAir PC Adapter	1.5W to tx at 100mW	.750W	.01W	FHSS
Aironet	LM3100	900mW to tx at 63mW	1.2W	.015W	FHSS

The transmit power will be linearly (slope=2) scaled to a theoretical minimum based on the minimum transmit requirements derived above. This may not be an accurate decrease in power in that according to the specifications listed above the total transmit power is not correlated with the power required by the radio itself. This power is more likely being used in the creation and modulation of the signal and protocol handling and would not decrease significantly with reduced transmit power. Using the lowest power solution from Table 7 the required total transmission power of DSSS increases to 214 mW and FHSS moves to 720 mW. For RSVP to transmit at 1mW will take 69mW.

In calculating 802.11 receiving time and power, the assumptions will be made that the amount of peer-peer communication is minimal, that clock synchronization is required every 100s, and that the AP initiates the poll. Therefore the only times the SC will setup to receive are for the 100s beacon (synchronization from AP) and for the poll-request acknowledgement and message acknowledgement sent by the AP during transmission once every 15 minutes. The beacon frame totals 92 Bytes and would take 736 μs to receive. The Acknowledgement frame totals 14 bytes and at 1Mbit/s would require 112 μs. It will be assumed, based on the table above, that being in the receive mode requires 1W. RSVP requires synchronization every 100s and has no acknowledgements. RSVP beacon frames (used for Synchronization) are composed of 30 Bytes, but on average the SC will only listen to the first 18 Bytes, since the rest of the information has a specific destination. At 200Kbit/s RSVP beacon frame reception will take 990μs and 129mW.

The remaining time will be spent by each SC in its associated sleep mode. Using the associated table above the lowest sleep parameter of 15mW will be used. For RSVP this factor drops to .1mW.

Taking into account the factors above, total power consumption estimates are calculated below. The following restates the total lifespan of each system.

$$\frac{2850mAH * .000114\frac{years}{hour} *}{TotalPower1cycle * Cycles\sin ayear} = \#ofyears \qquad (19\text{ repeat})$$

where

$$TotalPower1cycle = (T_t * P_t) + (T_r * P_r) + (T_s * P_s) \qquad (20\text{ repeat})$$

This equation, although simple and representative, does not easily take into account the differences in transmitting and receiving intervals. Therefore we will solve for the annual power consumption of each mode separately.

$$YearlyT_pDSSS = (656\mu s * 214mW) * \frac{35040 transmissions}{year} * \frac{3.171E-8 years}{s} = 1.559E-4mWyear$$

$$YearlyT_pFHSS = (593\mu s * 720mW) * \frac{35040 transmissions}{year} * \frac{3.171E-8 years}{s} = 4.744E-4mWyear$$

$$YearlyT_pRSVP = (1.93ms * 69mW) * \frac{35040 transmissions}{year} * \frac{3.171E-8 years}{s} = 1.480E-4mWyear$$

(25)

Doing the same for receive power:

$$YearlyR_pDSSS / FHSS = ((736\mu s * 1000mW) * \frac{315360 Beacon Receptions}{year} +$$
$$(112\mu s * 1000mW) * \frac{35040 Acknowledgements}{year}) * \frac{3.171E-8 years}{s} = 7.484E-3mWyears$$

$$YearlyR_pRSVP = ((990\mu s * 129mW) * \frac{315360 Beacon Receptions}{year} * \frac{3.171E-8 years}{s} = 1.277E-3mWyears$$

(26)

Taking into account the fact that the remainder of the time will be spent in sleep mode we get the following.

$$YearlyS_pDSSS = (3.153E13\mu s - ((656\mu s * 35040) + (160\mu s * 315360) + (112\mu s * 35040)))$$
$$* 15mW * \frac{3.171E-8 years}{s} = 14.997mWyears$$

$$YearlyS_pFHSS = (3.153E13\mu s - ((593\mu s * 35040) + (160\mu s * 315360) + (112\mu s * 35040)))$$
$$* 15mW * \frac{3.171E-8 years}{s} = 14.997mWyears$$

$$YearlyS_pRSVP = (3.153E13\mu s - ((1.93ms*35040) + (990\mu s*315360)))*.1mW*\frac{3.171E-8years}{s} = .1mWyears \quad (27)$$

From these figures we can get the total life span of each SC, based on its protocol, and disregarding sensing activity or processing.

$$DSSSlife = \frac{2850mAH*4.5v*.000114\frac{years}{hour}}{1.559E-4mWyears+7.484E-3mWyears+14.997mWyears} = 9.74E-2years \text{ or } 36 \text{ days}$$

$$FHSSlife = \frac{2850mAH*4.5v*.000114\frac{years}{hour}}{4.744E-4mWyears+7.484E-3mWyears+14.997mWyears} = 9.74E-2years \text{ or } 36 \text{ days}$$

$$RSVPlife = \frac{2850mAH*4.5v*.000114\frac{years}{hour}}{1.48E-4mWyears+1.277E-3mWyears+.1mWyears} = 14.42years$$

(28)

CHAPTER 4

RESULTS

In comparing the results to the requirements it easy to see that the only acceptable protocol is the RSVP protocol. To understand this result it is best to break down each individual factor in power consumption based on percentages. In looking at transmitted and received power we see that RSVP uses approximately the same amount of power as both versions of 802.11. This makes sense in that although 802.11 takes more power to complete these functions its higher data rates decrease the amount of time spent in these modes. The sleep mode power consumption is by far the largest power consumer. For both versions of 802.11 the module is in sleep mode over 400,000 times longer than all other modes combined. Since RSVP only consumes .1mW compared to 802.11's 15mW consumption it directly follows that the total operational time of RSVP is 150 times longer.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

IEEE 802.11 was established to take advantage of the cost savings and ease of use associated with wireless systems. Unfortunately 802.11 falls short in meeting the low power requirements of many applications not directly associated with typical LAN use (i.e. fixed power devices or commonly recharged units). This shortfall is becoming more evident with the explosion of a new market for wireless devices such as sensing units, home networked units, and portable personal devices. RSVP points out the power problems associated in trying to find devices that can support both medium range (>10m) wireless access and low power consumption.

The reason for comparing 802.11 against a proprietary protocol lies in their advantages and disadvantage in relation to the RSVP program. 802.11 is a robust, cost-effective solution in which multiple manufacturers offer compliant devices that meet or exceed essentially all RSVP communication's requirements. By investing in standard, market rich technology much of the growth and maintenance risks of the system are decreased. Instead of a small number of engineers from a single company attempting to foresee future system growth and system design, an entire industry is setup both to compete and coordinate on standardized growth. 802.11 standard devices also carry many capabilities that would allow communication capabilities not necessarily required by the RSVP program, but which may be required in the future, such as peer-to-peer information exchange, as well as multiple security features. Unfortunately the power consumption of these devices cannot currently meet this critical requirement of the RSVP program.

In initially setting out to write this thesis it was assumed that the protocol itself, specifically the modulation scheme of the physical layer and inter-layer message transfer, was responsible for the power consumption problems associated with IEEE 802.11. In completing the thesis it was discovered that this assumption is only partially true. As shown above the modulation techniques associated with each protocol play little role in overall power consumption, in regards to the infrastructure poll-only approach of RSVP. By maintaining strict medium access control (not to be confused with the MAC layer itself), the spread spectrum techniques, which safeguard IEEE 802.11 from interference, can still be used within the lower power environment of RSVP. This leaves two main factors that can actually be accounted for in IEEE 802.11's poor power performance, both of which I believe stem from the overall environment in which it was developed. IEEE 802.11 was initially developed to be a second option for companies looking to setup LAN services. The standard is extremely robust in its ability to deliver multiple services in a LAN environment. Due to this much thought is given to handling the both MAC to PHY convergence and medium control. Unfortunately, little attention was paid to the power requirements resulting from the numerous background messages that must be passed within each device to manage these services. In addition when the manufacturers setout to develop compliant devices, little thought was given to a power saving mode. These statements are substantiated in current research. Proxim currently released a miniature 802.11 standard device that decreases its sleep mode power consumption from 15mA to 2mA. Still more power than allowed for in the RSVP requirements, but heading in the right direction. Also, new BiCMOS WLAN chipsets developed by Phillips Semiconductor Inc, promise 34 mA in transmit mode, 21 mA in receive mode, as well as 1 μA in sleep mode, specifications that will surpass the requirements of RSVP. Validation for the low power need also comes in the form of a new IEEE standards committee. The IEEE 802.15 Working Group for Wireless Personal Area Networks (WPANs) is to release a new standard in the fall of 2000. A key requirement in this new standard is to reduce the power requirements associated with the robust MAC requirements of 802.11. This new standard, which has initially been based on the Bluetooth Special Interest Group (SIG) protocol, will allow for a special 100m transmit mode, which would meet the RSVP distance requirements.

In working on this thesis I have had the opportunity to expose myself to current events in the fast changing environment of medium range wireless communication. Since Charles Stark Draper Laboratories, Inc. granted me the time to undergo this work I feel it is my responsibility to make recommendations to the RSVP program. First I will state that I believe that the RSVP team at Draper initially made the correct decision in not choosing either Bluetooth or IEEE 802.11 standard equipment. Obviously 802.11 did not meet the requirements of the program and Bluetooth was a new technology whose first goals were focused on short-range communications. Based on new developments I now feel that the RSVP program should take a new look at the ability of the market to meet program requirements. The benefits associated with choosing standard equipment, some of which are stated above, are well known. It was stated in the RSVP overview that there are mobile units in the RSVP system that were not addressed in this paper. These mobile units are to be worn by the shipboard crew in order to monitor personnel location and health. It may be possible to choose new low power IEEE 802.11 equipment developed by Proxim, Phillips, and possibly other vendors, that will meet the RSVP SC requirements. It is expected that the IEEE 802.15 standard will be interoperable with 802.11. If this is the case 802.15 devices could be integrated with the personal status monitors and 802.11 access points to provide low cost, open market solutions to the RSVP program.

Wireless devices are just beginning to scratch the surface of a market that I believe has applications we have not even imagined. By writing this paper and researching current technologies I have just started to grasp the concepts by which these applications will be developed. I look forward to the future and to watching this "wireless world" develop.

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