28 kbps to 9 Mbps UHF Modems for Amateur Radio Stations

Following on the heels of their HSMM article in the Nov/Dec 2004 issue, the authors present a protocol suite for UHF modem use.

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Preface

High Speed Multimedia (HSMM) radio within Amateur Radio currently consists primarily of the deployment by hams of inexpensive, commercially available off the shelf equipment used for radio-based local area networks (RLAN). This gear is typically one of the IEEE 802.11 standard's radios that can achieve speeds as high as 54 Mbps. The frequencies used are in the upper end of the 2400 MHz amateur band, sometimes on 902 MHz and on rare occasions the 5000 MHz band.

Although some linked HSMM radio nodes now cover an entire community, what is needed for the HSMM network to continue to rapidly grow are other methods of achieving greater range than 2.4 GHz propagation normally allows.

Early last year the ARRL HSMM Working Group decided to form a number of Radio Metropolitan Area Networks (RMAN) Project Teams to investigate such methods. Two of these teams have made substantial progress: The RMAN-VPN Team (using the Internet to connect HSMM nodes) and the RMAN-UHF Team (using lower Amateur bands such as the 440 MHz band for such linking).

What follows is a set of proposed protocols for the HSMM Orthogonal Frequency Division Multiplexing (OFDM) Modem that will allow Radio Amateurs to have all-mode voice, text, data, and video high-speed digital communications on the VHF, UHF and SHF bands. We hope to begin alpha testing of the OFDM modem this year in at least four locations—Racine, San Antonio, Tampa and Detroit. We plan to use an ATV channel in the 440 MHz band operating in a digital image mode we call Amateur Digital Video (ADV).

The Modem Physical Layer

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1. Introduction

This document defines a set of physical layer protocols in the Open System Interconnection model for point-to-point and point-to-multi-point operation between stations operating in the Amateur Radio service. These stations may be fixed, land mobile or maritime mobile and use either directional or omnidirectional antennas in the UHF bands. This document describes the format and behavior of the protocol.

Six modems with different data rates are defined to fit the various regulatory requirements and band plans from 219 to 2450 MHz. The narrowest bandwidth was chosen to fit the current FCC regulations governing data transmission on the 219-220 and 420-450 MHz bands. The highest bandwidth was chosen to fit the largest channels allocated to data transmission in the ARRL band plan.

2. Physical Media

The physical medium interconnecting users is the electromagnetic spectrum. Only the UHF and higher-frequency amateur bands have sufficient space to allow high-speed digital links. This family of modems is designed for use in urban areas under line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. Modems may use both directional and omnidirectional antennas.

Radio propagation in an urban area is characterized by strong multi-path propagation. Propagation measurements indicate that multi-path delays range from 1 to 20 µs for LOS and NLOS paths in an urban environment. The signaling rate on the radio link is limited, as the symbol period must be much longer than the maximum multi-path delay. Since we want to communicate at a data rate much higher than the symbol rate, multiple carriers must be used. The carrier spacing must be chosen to prevent mutual interference and ensure that the data on each carrier is orthogonal. The modems described here use 4.8-kBaud symbol rates with 6 kHz carrier spacing. This provides a guard band of 41.7 µs between adjacent symbols. Most intersymbol interference exists within the guard band and can be ignored.

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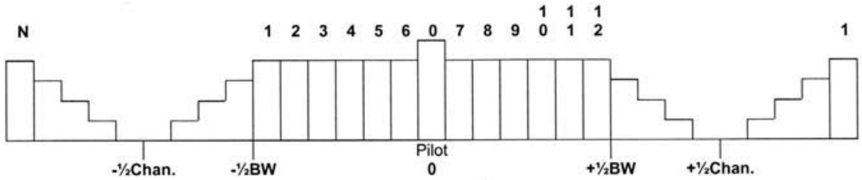

Fig 1—13-carrier transmission channel format (not to scale).

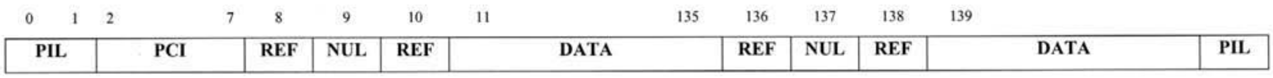

Fig 2—PHY PDU format (2 data blocks).

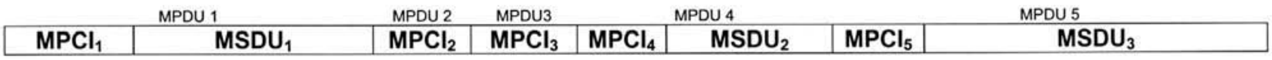

Fig 3—PHY-SDU with multiple MPDUs.

Table 1—Required minimum SNR for different modulation types (AWGN channel)

Symbol	*States per Symbol*						
Modulation	*2*	*4*	*8*	*16*	*32*	*64*	*256*
ASK	10	17	24	30	36	-	-
PSK	10	13	18	24	30	36	47
DPSK	11	15	21	27	33	39	51
QAM	-	13	-	20	-	26	32
DQAM	-	15	-	23	-	29	35

Table 2—Required frequency accuracy

Carriers	*96*	*288*
D8PSK	100.0 PPM	15.0 PPM
D256QAM	15.0 PPM	2.5 PPM

Table 3—Modem data rates for 4.8 kbaud and 6 kHz channel spacing

*Analog BPF**	*166 kHz @ ±1 dB*		*600 kHz @ ±1 dB*		*1.75 MHz @ -1 dB*	
FFT Sample Rate	96 ksps	192 ksps	384 ksps	768 ksps	1.536 Msps	3.072 Msps
No. Carriers	13	25	49	97	145	289
Signal Bandwidth	84 kHz	156 kHz	300 kHz	588 kHz	0.876 MHz	1.740 MHz
Channel Spacing	125 kHz	250 kHz	500 kHz	1000 kHz	1.500 MHz	3.000 MHz
DBPSK RC=1/2 Data Rate	*28.8 k*	*57.6 k*	*115.2 k*	*230.4 k*	*0.3456 M*	*0.6912 M*
DQPSK RC=2/3 Data Rate	*76.8 k*	*153.6 k*	*307.2 k*	*614.4 k*	*0.9216 M*	*1.8432 M*
D8PSK RC=2/3 Data Rate	*115.2 k*	*230.4 k*	*460.8 k*	*921.6 k*	*1.3824 M*	*2.7648 M*
D16QAM RC=5/6 Data Rate	192.0 k	384.0 k	768.0 k	1536.0 k	2.3040 M	4.6080 M
D64QAM RC=5/6 Data Rate	288.0 k	576.0 k	1152.0 k	2304.0 k	3.4560 M	6.9120 M
D256QAM RC=5/6 Data Rate	384.0 k	768.0 k	1536.0 k	3072.0 k	4.6080 M	9.2160 M

*Filter bandwidth is recommendation only.

3. Symbol Rate and Carrier Placement

A pilot carrier, used for timing information, is placed in the center of the carrier group. Half of the N data carriers are placed on each side of the pilot carrier and enumerated 1 through N from the lowest frequency to the highest frequency. Fig 1 shows 13 carriers with the main lobes of the carriers occupying the bandwidth, BW. The group delay must be flat over this bandwidth to minimize FFT sampling errors. Extending beyond that limit on either side are the minor lobes of the carriers. The channel spacing must be chosen so that the minor lobes of each channel's carriers are at an acceptably low level by the first carrier of the next channel.

Table 3 summarizes the various numbers of carriers and data rates for the modems. Carrier frequencies are accurate to ±100 PPM. The symbol rate shown includes a gap that is filled at the transmitter with a copy of the last ¼ of each tone. This provides a continuous waveform for the receiver FFT window even though there may be jitter. The receiver will normally sample the last part of the symbol cell to avoid inter-symbol interference that may exist in the first part of each symbol.

A number of options exist for modulating the data carriers including amplitude modulation (ASK), phase modulation (PSK) and a combination of the two (QAM). Each requires a different signal to noise ratio (SNR) to achieve a specific data rate. The SNR values summarized in Table 1 are those required for a 10^{-5} symbol error rate. Since each transmission consists of less than 11,520 symbols the block error rate can be expected to be less than 12% at these levels.

Table 2 shows the required frequency accuracy for different numbers of carriers and modulation types.

Fig 4—Data MPDU.

Table 4—PHY protocol control information (PCI) coding

PHY-PCI 012345	*Data Carrier Modulation*	*Coding Rate*	*Bits per 12 Carriers*
111111	DBPSK	1/2	6
010101	DQPSK	2/3	16
101010	D8PSK	2/3	24
111000	D16QAM	5/6	40
001110	D64QAM	5/6	60
100011	D256QAM	5/6	80

Table 5—Carrier amplitude as a function of quantity

Carriers	*1*	*13*	*25*	*49*	*97*	*145*	*289*
Amplitude (dBc):	0	-20	-23	-27	-30	-32	-36

Table 6—Puncture codes

Coding Rate	*Puncture Code 0*	*Puncture Code 1*	*Bits per 12 Carriers*
1/2	*1*	*1*	*6*
2/3	*10*	*11*	*8*
5/6	*10101*	*11010*	*10*

Six modulation types are defined for each of six modem bandwidths. Differential phase shift keying (DPSK) is used for the lowest three data rates to allow mobile operation in addition to fixed operation. As the station moves, the absolute phase varies as the strength and delay of multi-path rays vary so a fixed phase reference cannot be used. The highest three data rates are for fixed stations only. DQAM is used to compensate for phase rotation due to inaccuracies in carrier spacing.

All implementations of this modem must support a choice of DBPSK, DQPSK and D8PSK modulation. If QAM is supported, then a choice of DBPSK, DQPSK, D8PSK, D16QAM, D64QAM and D256QAM will be supported. The *italicized* data rates in Table 3 are those that must be supported for minimal compliance with this standard.

4. PHY-PDU Format

There are four special OFDM symbols used in the PHY-PDU. The null (NUL) symbol contains an unmodulated pilot carrier at the amplitude defined in Table 4 and no data carriers for one symbol period. The pilot (PIL) symbol is an unmodulated pilot carrier at maximum power (0 dBc) for one symbol period. The pilot carrier is used for frequency acquisition and Doppler shift correction.

The reference (REF) symbol allows the receiver to determine the starting phase and amplitude. The absolute phase of each carrier is set according to the formula:

$$\theta = 3.6315\ k^2$$

where k is the carrier index by frequency. The crest factor is less than 5 dB so the reference symbol shall be transmitted at 4 dB above the power levels in Table 4 to improve amplitude and phase estimation. The PCI symbols are ASK modulated REF symbols with a one at +4 dB above normal power levels and a zero at 2 dB below normal power levels using the patterns defined in Table 4. The use of REF symbols combats selective fading. The format of the PHY-PDU is shown in Fig 2.

The PHY-PDU begins with 2 PIL and 6 PCI symbols. The high amplitude single carrier allows the receiver to acquire carrier frequency lock more easily. The PCI symbols then specify the data carrier modulation as follows:

The PHY-PCI symbols have a minimum Hamming distance of 3 so 1 bit error correction is possible.

This is followed by the 3-symbol sequence REF-NUL-REF that is designed to allow the receiver to establish time synchronization under adverse conditions. Up to 125 symbols containing data may then be transmitted. If more data is to be transmitted, it is broken up into 125-symbol data blocks with the REF-NUL-REF sequence inserted in between blocks of data. This allows the transmitter and receiver clocks to resynchronize. Clock frequencies must be accurate to ±100 PPM. The last data block may be shorter than 125 symbols. The PHY-PDU ends with a PIL symbol.

Data is transmitted in the 12 to 288 outer carriers with PSK or QAM-modulated symbols. Five types of coding are used depending on the signal to noise ratio (SNR) on the link. 12, 24, 36, 48, 72 or 96 bits may be encoded in each 12-carrier group with rate 1/2, 2/3 or 5/6 forward error correction (FEC) coding. This results in data transfer rates of 1/2, 4/3, 2, 10/3, 5 or 20/3 times the number of data carriers times the symbol rate. If the number of data bits to be transmitted is less than the number of data carriers, zero bits will be added as padding. This will only be done on the last symbol in a frame.

User data bytes are serialized by placing the least significant bit into the bit stream first and the most significant bit into the bit stream last. FEC is provided by a rate ½ block convolutional code (BCC) with a constraint length of 7. The generator polynomials are $g_0 = 1011011_2$ and $g_1 = 1111001_2$. The code rate is then modified by ANDing with puncture code shown Table 6.

Encoded bits are mapped onto each OFDM symbol as follows. The first bit maps onto bit A of the lowest frequency carrier and the next onto bit A of the next higher frequency carrier until all carriers are covered. If higher-order modulation is being used, the next set of bits maps onto bit B of each carrier from lowest to highest frequency. If needed, the same mapping continues from lowest to highest frequency carrier for bits C, D, E, F, G and H. This mapping ensures that errors occurring on one carrier are spread out over the bit stream.

4.1 BPSK—One Bit per Carrier

Under very low SNR conditions, one bit is mapped on to each data carrier and all are transmitted in parallel in each symbol period as defined in Table 7. A zero bit is transmitted with normal carrier phase and a 1 bit is transmitted with inverted phase.

4.2 QPSK—Two Bits per Carrier

Under low SNR conditions, the data rate can be doubled with two data bits mapped onto each carrier as shown in Table 8. Dibit values are in Gray-code sequence so that a 90° phase error affects only one bit.

4.2 D8PSK—Three Bits per Carrier

Under moderate SNR conditions, the data rate can be tripled with three data bits mapped onto each carrier as shown in Table 9. Tribit values are in Gray-code sequence so that a 45° phase error affects only one bit.

4.4 16QAM—Four Bits per Carrier

When the SNR is higher, transmitting 4-bits per carrier quadruples the data rate. The bits are spread over the carriers in 4-bit groups using 16QAM modulation with a rectangular signal constellation as shown in Table 10. Each nibble is split into two with the least significant dibit modulating the in-phase carrier amplitude and the most significant dibit modulating the quadrature carrier amplitude.

4.5 64QAM—Six Bits per Carrier

When the SNR is very high, transmitting 6-bits per carrier results in a rate six times the base the data. The bits are spread over the carriers in 6-bit groups using 64QAM modulation with a rectangular signal constellation as shown in Table 11. Each hexbit is split into two tribits with the least significant tribit modulating the in-phase carrier amplitude and the most significant tribit modulating the quadrature carrier amplitude.

4.6 256QAM—Eight Bits per Carrier

When the SNR is extremely high, transmitting 8-bits per carrier results in a rate 8 times the base the data. The bits are spread over the carriers in 8-bit groups using 64QAM modulation with a rectangular signal constellation as shown in Table 12. Each byte is split into two nibbles with the least significant tribit modulating the in-phase carrier amplitude and the most significant tribit modulating the quadrature carrier amplitude.

5. PHY Service Interface

The physical layer service is defined to be compatible with IEEE 802.11-1999 section 12. The modem user accesses the physical layer service through a physical service access point PHY-SAP. This section describes the physical layer service offered to the user in terms of events, called service primitives, that cross the PHY-SAP.

5.1 Data Transmission

There are six service primitives associated with data transmission.

- The user issues **PHY-TXSTART.request** to start transmission of a data frame. The parameters are the number of data carriers and modulation type.
- The provider issues **PHY-TXSTART.confirm** when it is ready to receive user data bytes for transmission.
- The user issues **PHY-DATA.request** to transmit one byte of data. The parameter is one byte of user data and a maximum of 8,640 bytes may be transmitted in one PHY-SDU. This request is only valid between PHY-TXSTART.confirm and PHY-TXEND.request primitives.
- The provider issues a **PHY-DATA.confirm** when it is ready to receive another data byte.

Table 7—DBPSK encoding

Bit A	*Phase Shift*
0	0°
1	180°

Table 8—DQPSK encoding

Dibit B A	*Carrier Phase Shift*
0 0	0°
0 1	90°
1 1	180°
1 0	270°

Table 9—D8PSK encoding

Tribit C B A	*Carrier Phase Shift*
0 0 0	0°
0 0 1	45°
0 1 1	90°
0 1 0	135°
1 1 0	180°
1 1 1	225°
1 0 1	270°
1 0 0	315°

Table 10—16QAM encoding

Lower Dibit B A	*I Amp.*	*Upper Dibit D C*	*Q Amp.*
0 0	-0.70	0 0	-0.70
0 1	-0.23	0 1	-0.23
1 1	+0.23	1 1	+0.23
1 0	+0.70	1 0	+0.70

Table 11—64-QAM encoding

Lower Tribit C B A	*I Amp.*	*Upper Tribit F E D*	*Q Amp.*
000	-0.7	000	-0.7
001	-0.5	001	-0.5
011	-0.3	011	-0.3
010	-0.1	010	-0.1
110	+0.1	110	+0.1
111	+0.3	111	+0.3
101	+0.5	101	+0.5
100	+0.7	100	+0.7

Table 12—256-QAM encoding

Lower Nibble D C B A	*I Amp.*	*Upper Nibble G H F E*	*Q Amp.*
0000	-0.707	0000	-0.707
0001	-0.613	0001	-0.613
0011	-0.518	0011	-0.518
0010	-0.424	0010	-0.424
0110	-0.330	0110	-0.330
0111	-0.236	0111	-0.236
0101	-0.141	0101	-0.141
0100	-0.047	0100	-0.047
1100	+0.047	1100	+0.047
1101	+0.141	1101	+0.141
1111	+0.236	1111	+0.236
1110	+0.330	1110	+0.330
1010	+0.424	1010	+0.424
1011	+0.518	1011	+0.518
1001	+0.613	1001	+0.613
1000	+0.707	1000	+0.707

- The user issues **PHY-TXEND. request** to complete transmission of a frame.
- The provider issues **PHY-TXEND. confirm** when frame transmission is complete.

5.3 Data Reception

There are three service primitives associated with data reception.

- The provider issues **PHY-RXSTART. indication** to signal the start of a new data frame. The single parameter is RSSI which is the pilot carrier amplitude in dBnV.
- The provider issues **PHY-DATA. indication** to transfer one byte of user data. The user must accept data at the rate it appears at the PHY-SAP.
- The provider issues **PHY-RXEND. indication** to indicate the end of a data frame. The single parameter is RXERROR, which has one of the following values:

NoError. This value is used to indicate that no error occurred during PHY-SDU reception.

FormatViolation. This value is used to indicate that the format of the received PHY-SDU was in error. This condition is detected by a FEC error.

CarrierLost. This value is used to indicate that during the reception of the incoming PHY-SDU the carrier was lost and no further processing could be accomplished. This condition is detected by the absence of the final all zeros symbol.

UnsupportedRate. This value is used to indicate that a nonsupported number of carriers or modulation type was detected.

5.3 Clear Channel Assessment

There are three service primitives associated with clear channel assessment (CCA). These are used to hold off transmission when the channel is in use by another station.

- The user issues **PHY-CCARESET. request** when it wishes to reset the CCA logic.
- The provider issues **PHY-CCARESET.confirm** when the CCA logic is reset.
- The provider issues **PHY-CCA. indication** to indicate the presence or absence of RF energy in the currently selected channel. The single parameter is STATE, which has the value BUSY or IDLE.

6. PHY Protocol

This section describes the actions taken by this physical layer entity in response to stimulus from the physical media and physical service access point.

6.1 PHY-TXSTART.request

When a PHY-TXSTART.request is received, the receiver is disabled if this is a half-duplex link. The transmitter is then enabled and the center carrier is transmitted. The initial zero symbol is then transmitted and a PHY-TXSTART.confirm is issued to the user.

6.2 PHY-DATA.request

When a PHY-DATA.request is received, the data byte is saved and a PHY-DATA.confirm is returned to the user. Data bytes are accumulated until enough are present to transmit one symbol.

6.3 PHY-TXEND.request

When a PHY-TXEND.request is received, any required padding bytes are generated and the last symbol is transmitted. The pilot and data carriers are disabled. If this is a half-duplex link, the receiver is enabled. A PHY-TXEND.confirm is then issued.

6.4 Pilot Carrier Detect

If a pilot carrier is detected with an amplitude exceeding RSSI_CCA the receiver will attempt to synchronize to the carrier frequency and then to the symbol rate detected in the pilot carrier modulation. If carrier and symbol synchronization are achieved the receiver waits for the first symbol.

6.5 First Symbol

When data carriers appear, the first symbol is immediately decoded and interpreted as the value zero. A PHY-RXSTART.indication is issued with the received pilot carrier amplitude plus the maximum and current modulation type and number of carriers specified in the PCI and the receiver begins decoding data symbols using the rules specified in the PCI.

6.6 All Other Symbols

As the receiver decodes data symbols, PHY-DATA.indications are issued to the user with the value of the bytes encoded by the symbol. One symbol results in 1 to 240 PHY-DATA.indications.

6.7 Data Carrier Loss

When the data carriers disappear, a PHY-RXEND.indication (NoError) is passed to the user and the receiver waits for another symbol.

6.8 Pilot Carrier Loss

If the pilot carrier disappears during a period when there are no data carriers, a PHY-CCA.indication (IDLE) is passed to the user and the receiver waits for a pilot carrier with no data carriers. If the pilot carrier disappears during a period when data carriers are present, a PHY-RXEND.indication (CarrierLost) is issued and the receiver waits for a pilot carrier with no data carriers.

6.9 Noise Level Increase

If the receiver detects an increase in RF energy within the channel that is not the pilot carrier, but exceeds RSSI_CCA for more than one symbol period, it sets CCA_STATE to BUSY and issues a PHY-CCA.indication (BUSY).

6.10 Noise Level Decrease

If CCA_STATE is BUSY and receiver detects an decrease in RF energy to a level less than RSSI_CCA for a period exceeding 16 symbol periods, it sets CCA_STATE to IDLE and issues a PHY-CCA.indication (IDLE).

7. PHY Management Interface

The management interface provides a means for the user to configure the modem and to collect performance information. The service primitives are defined in this section. Management operations apply to all local PHY-SAPs.

7.1 Configuration Management

The service primitive **PHY-CONFIGURE.request** transfers configuration data to the modem. There are three parameters, RSSI_CCA, TM and TC. The values and semantics of TC and TM are defined in section 5 of this document. RSSI_CCA is the CCA logic threshold in dBnV. TC and TM will retain a value of zero if the specified option is not implemented.

7.2 Performance Management

There are two service primitives that are used to request modem status information.

- The user issues a **PHY-STATUS. request** to request the current value of counters held within the modem.
- The provider issues a **PHY-STATUS.confirm** to return the current value of all management objects. The management objects are 32-bit unsigned binary values and are not modified when read. The following values are returned:

CCA_STATE – clear channel assessment logic state (BUSY or IDLE).

RSSI_CCA – RF energy level above which channel is declared BUSY.

RSSI_IDLE – average amplitude of RF energy in channel during IDLE states.

RSSI_BUSY – amplitude of RF energy in channel when last PHY-CCA.indication (BUSY) was issued.

RSSI_DATA – signal level of pilot carrier when last PHY-RXSTART. indication issued in dBnV (dB above 1 nanovolt).

PHS_ERR – maximum difference in phase between expected and actual value for last symbol received ($2^{32}=2\pi$).

AMP_ERR - maximum difference in amplitude between expected and actual value for last symbol received ($2^{32}=\pm1$).

PCI_LAST – value of last received PCI field (bits 31-3 are zero).

The following objects are counters:

TIME – increments every symbol period.

CARRIER_DETECT – increments when a PHY-CCA.indication with a value of BUSY is issued.

PCI_ILLEGAL – increments when an illegal value is detected in PHY-PCI.

FEC_DETECT – increments when a transmission error is corrected by FEC.

FEC_ERROR – increments when a transmission error cannot be corrected.

FRAMES_RECEIVED – increments when a PHY-RXEND.indication is issued.

BYTES_RECEIVED – increments when a PHY-DATA.indication is issued.

FRAMES_TRANSMITTED – increments when a PHY-TXEND.confirm is issued.

BYTES_TRANSMITTED – increments when a PHY-DATA.confirm is issued.

All management object values (including counters) are reset to a value of zero when power is applied to the modem.

8. Recommended Operating Frequencies

Operating frequencies must be selected to fit with existing ARRL band plans and FCC regulations. There are no restrictions on occupied bandwidth for data transmission above 902 MHz. In the 219-220 and 420-450 MHz bands, the maximum occupied bandwidth for data transmission is 100 kHz. However, in the 420-450 MHz band, bandwidths of up to 6 MHz may be used for amateur television, including digital amateur television (DATV). The following frequencies are recommended for operation of the OFDM modems specified in this document.

Table 13—Recommended frequencies

Band	*Sub-Band*	*No. Chan.*	*Channel Spacing*
125 cm	219 - 220 MHz	8	125 kHz
70 cm	420 - 423 MHz	12*	250 kHz
	423 - 426 MHz	1**	3.00 MHz
33 cm	903 - 906 MHz	1	3.00 MHz
	915 - 918 MHz	1	3.00 MHz
23 cm	1,248 - 1,252 MHz	4	1.00 MHz
	1,288 - 1,294 MHz	2	3.00 MHz
	1,297 - 1,300 MHz	1	3.00 MHz
13 cm	2,300 - 2,303 MHz	1	3.00 MHz
	2,396 - 2,399 MHz	1	3.00 MHz

*13 carriers for data transmission or 25 carriers for DATV

**Point-to-point DATV or experimental license for data transmission

UHF Modem MAC Sublayer for Amateur Radio Stations

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Date: 2004-5-6
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1. Introduction

This document defines a medium access control (MAC) sublayer entity in the Open System Interconnection model for point-to-point and point-to-multi-point operation between fixed and mobile stations operating in the amateur radio service. This document defines the protocol implemented by this MAC entity.

The Amateur Radio service has the following unique requirements for a MAC service and protocol:

The radio links can cover a wide area. Transmitter and receiver antennas mounted at a 90 foot height above average terrain (HAAT) can provide can provide communication over a 50 mile path. A station located on a mountaintop at 1500 feet HAAT has a radio horizon of 100 miles.

The ARS requires efficient multi-cast operation. A net can have over 100 stations participating that must all be able to receive transmissions from the net control station and from each other.

Radio communication is subject to fading that results in bursts of errors. Efficient operation requires that the error rate be minimized on each communication link.

The coverage area of Amateur Radio stations results in propagation times that approach one millisecond. Carrier-sense multiple access (CSMA) techniques are not sufficient to control medium access so some form of polling must be used. The radio channel characteristics dictate error correction but traditional ARQ techniques do not work for multicasting. Consequently, the MAC entity must incorporate forward error correction (FEC) to provide a reliable multicast service. Since all stations are not in range of each other, the net control (primary) station must have the capability of forwarding MAC protocol data units (MPDUs) to all other (secondary) stations to achieve full connectivity. FEC required long data units to work effectively but many applications will transmit short data blocks. The MAC protocol must support concatenation of short MPDUs into a longer physical service data unit (PHY-SDU).

2. MAC Service Interface

The MAC service defined in this document is designed for a network of stations that all operate on the same frequency and at the same symbol (baud) rate. The available data rates on each station may vary due to differing sets of capabilities, but all neighboring stations must have a common baud rate and compatible modulation.

The primary purpose of the MAC entity is to transfer blocks of user data called MAC service data units or MSDUs. A MSDU consists of 1 to 1,536 bytes of user data that is sent from a source address to a destination address. Addresses are six bytes in length and are formed from the ARS call signs of individual stations or the name of a multicast group. Three service primitives are used to transfer user data:

The user issues an MA-UNITDATA.request when it wishes to transmit a MAC service data unit (MSDU). The parameters are the destination address, source address, length and 1 to 1,536 bytes of user data.

The provider issues an MA-UNITDATA-STATUS.indication when the user data plus MAC protocol control information (PCI) is fully processed and the MAC entity is available for further data transmission. The single parameter is transmission status, which may have the value TRANSMITTED or LOCAL_ERROR.

The provider issues an MA-UNITDATA.indication when a complete MSDU has been received. The parameters are the destination address, source address, length and 1 to

1,536 bytes of user data.

3. MPDU Format

The MAC entity will concatenate multiple MAC protocol data units (MPDUs) for transmission in one PHY-SDU whenever possible. Each MPDU consists of MAC protocol control information (MPCI) and, optionally, a MAC service data unit (MSDU). Fig 3 shows an example with five MPDUs where three contain MSDUs. The maximum PHY-SDU length is 8,640 bytes.

3.1 Data MPDU

A Data MPDU transports a complete MSDU. It consists of 21 bytes of MPCI containing the address and type fields followed by a variable-length user-data field as shown in Fig 4. The MPCI fields are defined in Table 14. DA, SA and L are obtained from the MAC service user while IA is generated by the MAC entity. IA is the next destination address while DA is the ultimate destination address.

3.2 Token MPDU

A Token MPDU contains the address of the next secondary station to transmit as shown in Fig 5 and Table 15.

T3.3 RSSI MPDU

A RSSI MPDU reports the received signal strength indication (RSSI) for one or more transmitting stations at a particular receiving station as shown in Fig 6 and Table 16. The TA and RSSI fields are repeated N times. The C and M fields indicate the transmitter capabilities at the reporting station.

3.4 MAC Address Format for Amateur Radio Stations

A modem implementation conformant to this standard shall use the locally administered ANSI/IEEE 802 48-bit address format and addresses shall be formatted as shown in Fig 7. Source addresses must be individual addresses.

The X bit shall be 0 for individual addresses and 1 for group addresses. Each address shall consist of exactly seven characters whose values are in fields C0 through C7. Each shall be encoded in 6-bit ASCII as shown in Table 17. Allowable characters are the Latin letters A through Z (case insensitive), the decimal numbers 0 through 9 and the space character.

Multicast addresses are group addresses that start with a letter or number and must consist of seven characters.

Individual addresses shall start with a letter or number and fields C0 through C5 shall be the amateur radio service (ARS) call sign assigned to the control operator. Call signs shorter than 6 characters shall be padded at the right end with spaces. The last character is an extension field. If only one modem is under control of the licensed operator or trustee, C6 shall be a space character. If more than one modem is under the control of the licensed operator or trustee, C6 shall be a non-space character.

4. Block Error Correction Code

The radio communications channel is subject to fading and impulse noise that may introduce errors in bursts. The error correction provided in the physical layer may be overwhelmed and bytes containing errors may be delivered to the MAC sublayer. A MAC-level block error correction code generates additional error correction information and distributes it over many symbols to allow correction of burst errors and increase the number of MAC-PDUs delivered to the user. This section describes the block error correction code.

A Reed-Solomon code with a symbol width of one byte, a block length of 255 bytes, a maximum data field

Table 14—Data MPDU fields

Field	*Bytes*	*Semantics*
IA	6	Intermediate MAC Address.
DA	6	Destination MAC Address.
SA	6	Source MAC Address.
L	2	802.3 Length field.
MSDU	1-1536	User data.

Table 15—Token MPDU fields

Field	*Bytes*	*Semantics*
PA	6	Primary station MAC address.
N	1	0 if token sent to PA, 1 if token sent to SA.
SA	6	Secondary station MAC Address if N = 1.

Table 16— RSSI MPDU fields

Field	*Bytes*	*Semantics*
RA	6	Reporting station MAC address.
C	1	Maximum number of carriers divided by 12.
M	1	Maximum number of bits per 12 carrier group (6-80).
N	1	Number of RSSI reports (0-255).
TA_N	6	Transmitter MAC address.
SNR_N	1	SNR of TA_N pilot carrier at RA in dB.

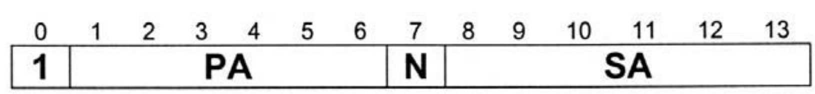

Fig 5—Token MPDU.

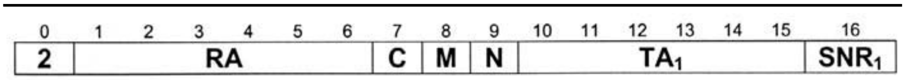

Fig 6—RSSI MPDU with one signal report.

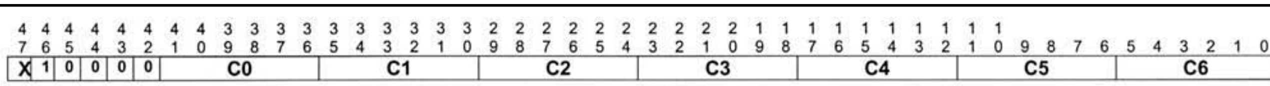

Fig 7—Amateur Radio subnetwork address format.

width of 239 bytes and a Galois field polynomial of 100011101_2 is used. This code will correct errors in as many as 8 symbols per block with an overhead of only 3.1%. When 239 data bytes are available for transmission, an encoded block of 255 bytes is generated. If the end of the PHY-SDU is reached and the number of data bytes to be transmitted is less than 239, a shortened code block is generated.

5. MPDU Forwarding

When the MAC entity receives a Data MPDU it must decide whether to deliver it locally, forward it to an adjacent station or discard it. The decision is made using the information maintained in the Neighbor Table in each station. The forwarding procedure depends on the type of destination address (individual or multicast) and the type of station (primary or secondary) involved.

Normal Forwarding: If the destination address is not a multicast address, the entries in the RSSI Table for all destination addresses are examined. If the destination addresses is the local station address, the user data is delivered to the local user at the MAC SAP. If the destination address is in the Neighbor Table, the MPDU is forwarded by setting the IA field to the destination address and transmitting the modified MPDU when this station has the permission to transmit a token. If the destination address is not in the Neighbor Table, the MPDU is forwarded by setting the IA field to the primary station address and transmitting the modified MPDU when this station has the permission to transmit a token. If this is the primary station, the MPDU is discarded.

Multicast Forwarding: If the destination address is a multicast address and this is a secondary station, the MPDU is forwarded by setting the IA field to the primary station address and transmitting the MPDU when this station has the permission to transmit a token. If the destination address is a multicast address and this is the primary station, the MPDU is forwarded by setting the IA field to the destination address and transmitting the modified MPDU when this station has the permission to transmit a token.

Each MAC entity makes decisions on the modulation method and number of carriers to use when transmitting to adjacent stations. It uses SNR data from the Neighbor Table entries for the adjacent stations that are to receive the PHY-SDU to select the modulation type and number of carriers to be used. The lowest SNR value is used to make the decision. The modulation type and number of carriers are selected based on the required SNR defined the physical layer standard. The MAC entity then checks the maximum allowed by the adjacent stations that are to receive this PHY-SDU. If the number of carriers selected is not supported by any one of these adjacent stations, the number of carriers is set to the maximum supported by all these stations and the modulation type is re-evaluated. The modulation type is then examined for each of these adjacent stations and if it is not supported, the number of bits per carrier is set to the minimum supported by all of these stations. The PHY-SDU is transmitted when the station receives permission in a Token MPDU.

6. Media Access Control

Access control is achieved via a token-passing mechanism. One station is the primary station that periodically transmits a token MPDU to selected secondary stations. The token MPDU is usually contained in a PHY-SDU that includes data transmissions to secondary stations. This token confers the right to transmit to the specified secondary station as shown in Fig 8.

The primary station transmits the token periodically to poll the secondary stations whose addresses are stored in its RSSI Table. After transmitting the token, the primary station monitors the channel status via PHY-CCA indications. If the medium is idle for more than two maximum length PHY-PDU times, the token is assumed to be lost and the primary station polls the next secondary station in the Neighbor Table.

Alternate primary stations (which may otherwise be secondary stations) may be configured. Each alternate primary station resets the ALT_PRI timer when it is passed the token. If the ALT_PRI timer ever expires, that station becomes the primary. The timer values for the first, second and third primaries are 0, 220 (1,048,576), and 221 (2,097,152) symbol periods.

7. RSSI Distribution

The Neighbor Table in the MAC MIB must be constantly refreshed with information on the communications paths between stations. The primary station polls all secondary stations by periodically transmitting an RSSI MPDU that contains the secondary station's pilot carrier amplitude at the primary station. Each secondary station broadcasts the received pilot carrier SNR by taking its idle time RSSI and the pilot carrier RSSI and calculating the SNR of the pilot carriers of all adjacent (i.e. heard) stations. The SNR information is then broadcast in an RSSI MPDU. Secondary stations that do not respond to this poll 4 times in a row are deleted

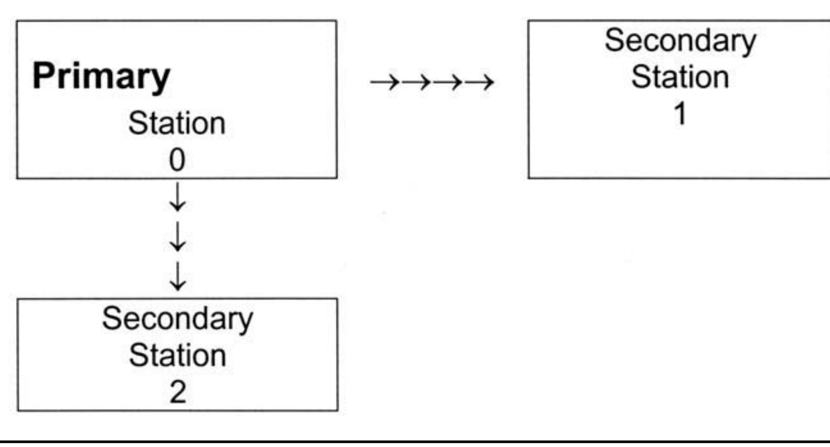

Fig 8—Token passing.

MAC Address	SNR	C	M
3ABC78	15	6	3
1465A7	23	12	6
A7779B	11	3	3

Fig 9—Neighbor Table.

from the primary station's Neighbor Table. The polling interval is every 2^{16} (65,536) symbol periods. Fig 9 is an example of a Neighbor Table.

The Neighbor Table also contains the transmitting capabilities of each neighboring station. C is an unsigned number from 0 to 255 giving the maximum number of carriers that the station can transmit divided by 4. M is an unsigned number from 0 to 15 giving the maximum number of bits per carrier that the station can transmit.

8. MAC Protocol

This section describes the actions taken by this MAC sublayer entity in response to stimulus from the underlying physical service access point (PHY-SAP) and the user connected to the MAC service access point (MSAP).

8.1 PHY-CCA.indication

When a PHY-CCA.indication with a value of BUSY is received transmission of MPDUs is inhibited. When a PHY-CCA.indication with a value of IDLE is received, the background noise level is stored.

8.2 PHY-RXSTART.indication

When a PHY-RXSTART.indication is received, the MAC receiver entity prepares to receive and decode bytes and stores the pilot carrier RSSI.

8.3 PHY-DATA.indication

When a PHY-DATA.indication is received the data byte is transferred to the FEC decoder logic. The output is monitored for incoming MPDUs. If there are uncorrectable errors in an MPDU, the received MPDU is discarded. Otherwise, Data MPDUs are forwarded according to the process described in section 5. Each correctly decoded MPDU with the address of the local station results in a MAC-DATA.indication. RSSI MPDUs are used to update the Neighbor Table and, if received at a secondary station, cause an RSSI MPDU to be queued for transmission to the primary station.

8.4 PHY-RXEND.indication

When a PHY-RXEND.indication is received, the MAC entity discards any partial MPDU and checks for a Token MPDU. The primary station address is set by the Token MPDU. If the token specifies the local station as the secondary station with permission to transmit, CCA is checked and transmission of any accumulated MPDUs begins. A token MPDU is always sent to the primary station as part of the PHY-SDU.

8.5 MAC-DATA.request

When a MAC-UNITDATA.request is received, the MPDU is formatted and stored. The total PHY-SDU size, in bytes, is then calculated and this information is stored until the station receives permission to transmit.

8.6 Receipt of Token MMPDU

If the token MMPDU contains the local station address the MAC transmitter entity checks the channel status, waits for a value of IDLE, and issues a PHY-TXSTART.request with the appropriate carrier and modulation parameters.

8.7 PHY-TXSTART.confirm

When a PHY-TXSTART.confirm is received, the MAC entity issues the first PHY-DATA.request.

8.8 PHY-DATA.confirm

When a PHY-DATA.confirm is received, the MAC entity checks for more bytes to transmit. If so, the MAC entity issues a PHY-DATA.request. A MAC-UNITDATA-STATUS.indication is issued as transmission of each Data MMPDU completes. When all are transmitted a PHY-TXEND.request is issued.

8.9 PHY-TXEND.confirm

When a PHY-TXEND.confirm is received the receiver is enabled.

USB Interface for UHF RF Modem

Version: draft 2
Date: 2004-5-6
Author: John B. Stephensen, KD6OZH

1. Introduction

This document defines the user interface for an RF modem using the UHF bands in the Amateur Radio service. The interface is provided via the Universal Serial Bus (USB).

Table 17—ARS 802-style address character set and encoding.

	Bits 5-4			
Bits 3-0	*00*	*01*	*10*	*11*
0000	(space)	0		P
0001		1	A	Q
0010		2	B	R
0011		3	C	S
0100		4	D	T
0101		5	E	U
0110		6	F	V
0111		7	G	W
1000		8	H	X
1001		9	I	Y
1010			J	Z
1011			K	
1100			L	
1101			M	
1110			N	
1111			O	

2. MAC Service and Interface

To provide compatibility with the existing LLC sublayer and network layer implementations, the service shall be as defined in ANSI/IEEE 802.2-1998 section 2.3. The user interface shall be as defined for the data class interface in the Ethernet Networking Control Model in "Universal Serial Bus Class Definitions for Communication Devices", version 1.1, 1999-1-19. This section provides a summary of the information in these documents.

The primary purpose of the modem is to transfer blocks of user data called MAC service data units or MSDUs. A MSDU consists of 1 to 1,536 bytes of user data that is sent from a source address to a destination address. Addresses are six bytes in length and their values may be a multicast address (a group of stations) or an individual address (exactly one station). Three service primitives are used to transfer user data:

The user issues a MAC-UNITDATA.request when it wishes to transmit data. The parameters are source address, destination address, user data, priority and service class.

The provider issues a MAC-UNITDATA.indication when a complete SNSDU has been received. The parameters are the source address, destination address, user data, reception status, priority and service class.

These service primitives are mapped into MAC interface data units (MIDUs) that are carried by one or more USB bulk data transfers. An OUT transfer is a request and an IN transfer is an indication. The service parameters are formatted as defined in ANSI/IEEE 802.3-2002 for the destination address, source address and length fields of a MAC protocol data unit (MPDU). A complete MIDU consists of zero or more bulk data transfers of maximal length followed by one bulk data transfer with a length less than the maximum. The bulk transfer with a length less than maximum (including zero) is the end delimiter for the MIDU.

3. Management Service and Interface

The layer and system management interface shall be as defined for the communication class interface in the Ethernet Networking Control Model in "Universal Serial Bus Class Definitions for Communication Devices",

Destination Address	Source Address	Length	User Data	User Data	User Data

Fig 10—MIDU format.

Table 18—Ethernet statistics

Offset	*Field Name*	*Description*
D0	XMIT_OK	MPDUs transmitted.
D1	RCV_OK	MPDUs received.
D2	XMIT_ERROR	MPDUs not transmitted.
D3	RCV_ERROR	Total received MPDUs discarded.
D4	RCV_NO_BUFFER	MPDUs discarded due to buffer overflow.
D5	DIRECTED_BYTES_XMIT	MSDU data bytes transmitted to individual address.
D6	DIRECTED_FRAMES_XMIT	MSDUs transmitted to individual address.
D7	MULTICAST_BYTES_XMIT	MSDU data bytes transmitted to multicast address.
D8	MULTICAST_FRAMES_XMIT	MSDUs transmitted to multicast address.
D9	BROADCAST_BYTES_XMIT	MSDU data bytes transmitted to broadcast address.
D10	BROADCAST_FRAMES_XMIT	MSDUs transmitted to broadcast address.
D11	DIRECTED_BYTES_RCV	MSDU data bytes received from individual address.
D12	DIRECTED_FRAMES_RCV	MSDUs received from individual address.
D13	MULTICAST_BYTES_RCV	MSDU data bytes received from multicast address.
D14	MULTICAST_FRAMES_RCV	MSDUs received from multicast address.
D15	BROADCAST_BYTES_RCV	MSDU data bytes received from broadcast address.
D16	BROADCAST_FRAMES_RCV	MSDUs received from broadcast address.
D17	RCV_CRC_ERROR	MPDUs received with FEC error.
D18	TRANSMIT_QUEUE_LENGTH	Number of MPDUs waiting for transmission.
D19	RCV_ERROR_ALIGNMENT	Partial MPDUs received at end of PHY-SDU.
D20	XMIT_ONE_COLLISION	Token MPDUs received (secondary) or transmitted (primary).
D21	XMIT_MORE_COLLISIONS	0
D22	XMIT_DEFERRED	Number of times transmission delayed by CCA busy.
D23	XMIT_MAX_COLLISIONS	0
D24	RCV_OVERRUN	Received MSDUs discarded due to lack of buffer.
D25	XMIT_UNDERRUN	0
D26	XMIT_HEARTBEAT_FAILURE	0
D27	XMIT_TIMES_CRS_LOST	0
D28	XMIT_LATE_COLLISIONS	0
D29	undefined	Number of Neighbor Table entries.
D30	undefined	RSSI MPDUs transmitted.
D31	undefined	RSSI MPDUs received.

version 1.1, 1999-1-19. The following functions shall be implemented:

- SetEthernetMulticastFilters – a minimum of sixteen 48-bit addresses of any format shall be supported.
- SetEthernetPacketFilter–PACKET_TYPE_ALL_MULTICAST and PACKET_TYPE_ PROMISCUOUS required.
- GetEthernetStatistic – all selector codes shall be supported. Some counters may be mapped to non-802.3 information.
- The SetEthernetMulticastFilters request shall be used to set the RF modem frequency and register the 48-bit individual address and any group addresses used to identify the station.

The first entry shall be the modem frequency in kHz represented as a binary coded decimal integer. There is no hardwired MAC address and the modem will not transmit until an individual MAC address is configured.

The primary station shall be configured by including an entry with a value of FFFFFFFFFFFF$_{16}$. The alternate primary station is FFFFFFFFFFFF$_{16}$ and FFFFFFFFFFFF$_{16}$.

The statistics shown in Table 18 must be supported.

For More Information

If you have any questions about the OFDM modem or other topics regarding high-speed digital or multimedia operation, the HSMM Working Group can help you get started in this exciting part of amateur radio. You can subscribe to the ARRL IEEE 802.11b Mail List at Texas A & M University. To subscribe to this public list, go to the URL: **listserv.tamu.edu/archives/arrl-80211b.html** and select *Join or leave the list,* or see **www.arrl.org/hsmm/**.

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John Stephensen, KD6OZH, became interested in radio at age 11, when his grandfather bought him a crystal radio kit. During the 1960s, he built several HF receivers using vacuum tubes and other parts procured from discarded black-and-white TV sets. After attending the University of California, he and two friends founded PolyMorphic Systems, a supplier of personal computer kits, and later manufactured computers, in 1975. In 1985, he was cofounder of Retix, a networking hardware and software supplier. John received his Amateur Radio license in 1991 and has been active on bands from 7 MHz to 24 GHz, with interests including HF and microwave DXing and contesting. He has also been active on packet, satellites and on the HF bands using several digital modes. John has always designed and built his own Amateur Radio gear, some of which has been described in QEX *articles in recent years. His latest projects have centered on high-speed digital communication using DSP.* □□