

A Software Defined Radio for Mesh Networks

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Abstract

This paper describes an FPGA-based SDR transceiver that may be used for ad-hoc wireless mesh networking on the VHF and UHF amateur bands. The architecture allows simultaneous use of two channels, a fixed frequency control channel and a variable frequency data channel, to overcome bandwidth limitations and prevent inter-node interference. Multiple transceivers may cooperate to form a layer-2 mesh network that looks like an Ethernet switch to users. Internal software implements derivatives of AODV and ODMRP with source multi-point relays for efficient unicast, broadcast and multicast transmission.

Keywords: FPGA, SDR, OFDM, packet radio

Introduction

In the 2010 DCC [1], I provided a paper describing an FPGA-based transceiver module that was developed for amateur radio use. It contained an 80 Msps ADC and DAC with an FPGA implementing a 16-bit soft CPU plus coprocessors for downconversion, demodulation, modulation and upconversion of 1-30 MHz signals. A 100 Mbps Ethernet port and an RS-485 serial port provided communication with personal computers and other digital devices. Expansion connectors provided for control of RF circuitry and allowed use with an external audio codec for analog voice modes. The on-chip processor was used to implement analog SSB, AM and FM voice modes.

I was a member of the ARRL High-Speed Multimedia (HSMM) Working Group chaired by John Champa, K8OCL (SK) and volunteered to develop an RF modem to augment IEEE 802.11 (WiFi) equipment and provide longer-distance communications links. An OFDM modem was implemented and tested using transverters for the 6-meter and 70-centimeter amateur bands. Since a software-defined radio was used, experimentation could easily be carried out with different channel sizes and data rates. This allowed creation of point-to-point links with ten different user data rates from 2.4 kbps in a 3 kHz channel to 900 kbps in a 1 MHz channel.

Recently, I updated the design with a larger FPGA and an ADC with more dynamic range. The DCP-3 used an Analog Devices AD9236 12-bit ADC while the new DCP-6 uses an AD9255 14-bit ADC with internal dithering logic. This increases the receiver dynamic range from 91 to 110 dB. The old DCP-3 board used a Xilinx XC3S500E FPGA with 9,000 4-input logic elements, 20 multipliers and 40 KB of RAM. The new DCP-6 uses a XC6SLX25 with 15,000 6-input logic elements, 38 multipliers and 104 KB of RAM. Two sets of transceiver hardware are implemented that may be used simultaneously. In addition, the amount of memory available to the soft processor has been quadrupled and its instruction set is more memory efficient.

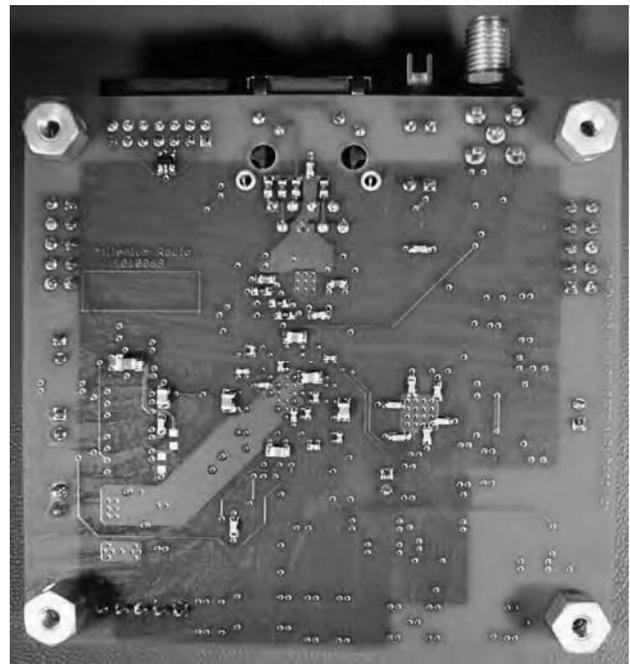
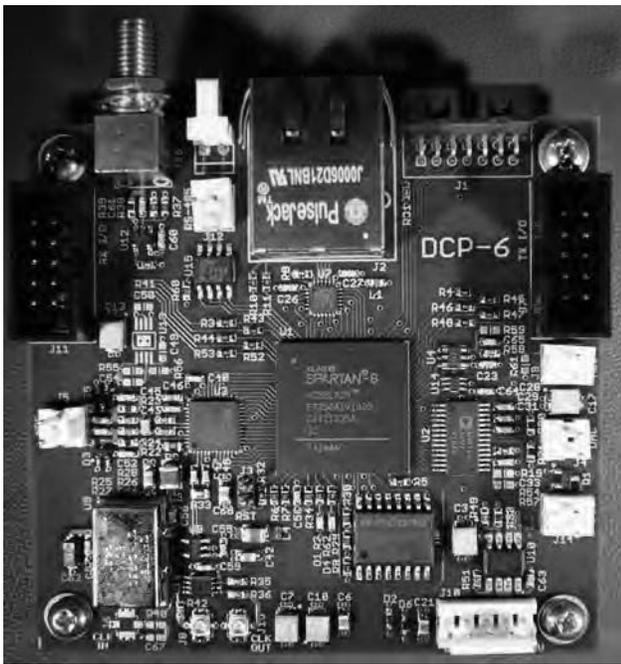


Figure 1 – DCP-6 PCB

The DCP-3 had limited memory for software and could only implement MAC (media access control) protocols for point-to-point or broadcast links. Data emissions are limited by FCC regulations to a 20 kHz bandwidth in the 6 and 2 meter bands or a 100 kHz bandwidth in the 125 and 70 cm bands. This results in a 19.2 kbps or 96 kbps link being shared among multiple nodes. I was not happy with the functionality achieved for the hardware cost. The DCP-6 takes advantage of 45-nm FPGA technology to provide much greater functionality for a minor increase in cost. Dual transceivers allow the use of multiple channels for higher aggregate data rates and additional memory allows operation over multiple hops for longer distances.

OFDM Modem

The OFDM modem uses two layers of error-correcting codes to ensure the reliable transfer of data. This is especially important for broadcast and multicast data where it would be very inefficient for all of the recipients to transmit acknowledgements. The inner code minimizes the SNR required by the data link and the outer code compensates for fading.

The modem is optimized for use with amateur high-power amplifiers. It uses trellis-coded differential 8-PSK modulation with a rate-2/3 inner error correcting code (ECC). PSK has a probability distribution function (PDF) that peaks at lower magnitude than QAM constellations as shown in figure 2. This allows signal peaks to be clipped at a lower level than QAM waveforms to reduce the peak-to-average power ratio (PAPR). The error-correcting code removes any errors introduced by clipping although errors due to clipping are far more infrequent than those induced by noise on the RF link. The lower PAPR allows more efficient use of high-power amplifiers and higher signal-to-noise ratios at the receiver for longer range data links. Figure 3 shows the results of RF clipping in a DCP-6 configure for a 500 kHz channel – note the scale change between clipping and no clipping oscilloscope photographs.

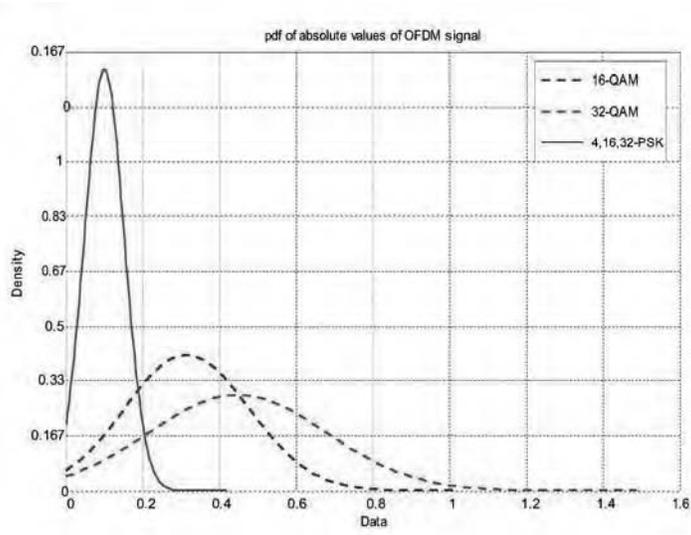


Figure 2 – PDF for Different OFDM Subcarrier Modulation Types

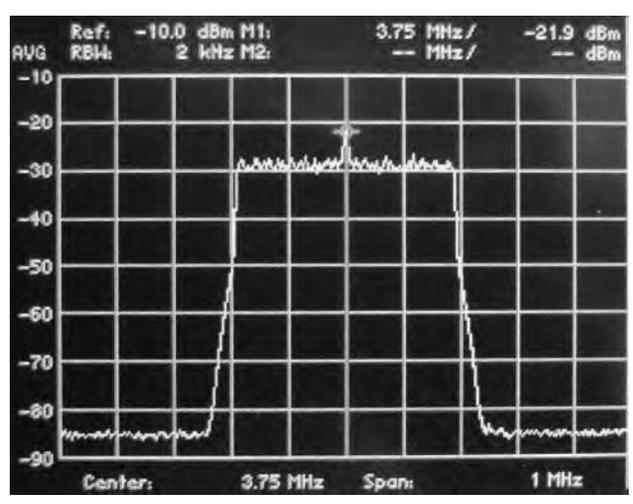
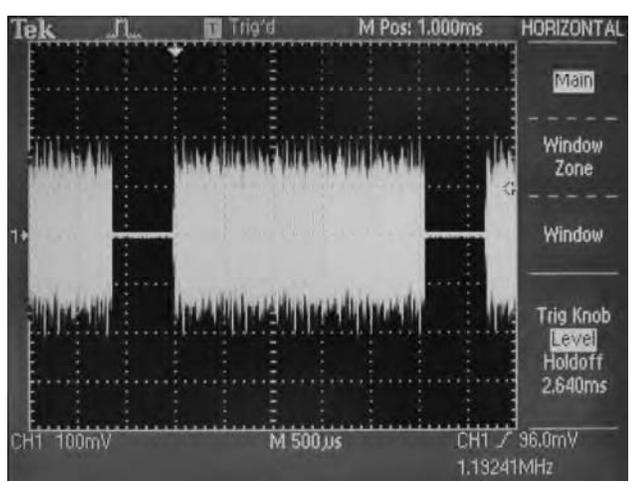
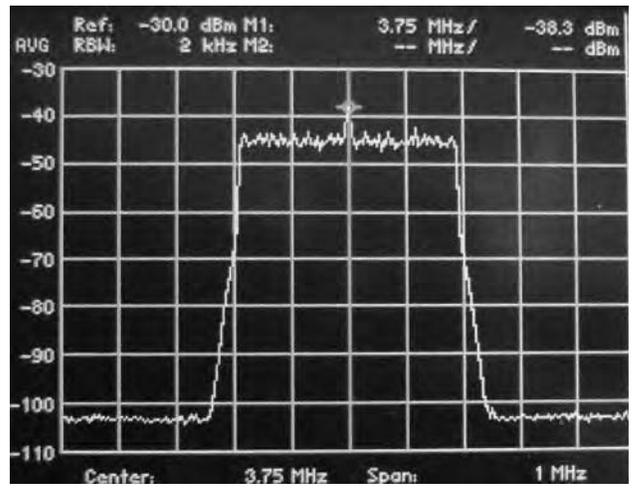
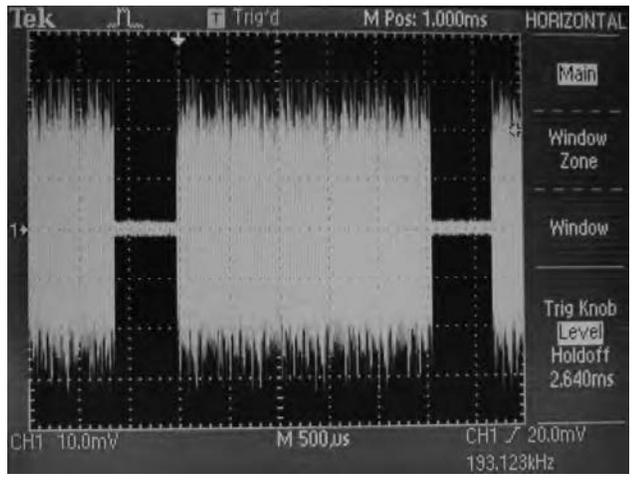


Figure 3 – DCP-6 Output with no Clipping (top) and 18 dB of RF Clipping (bottom)

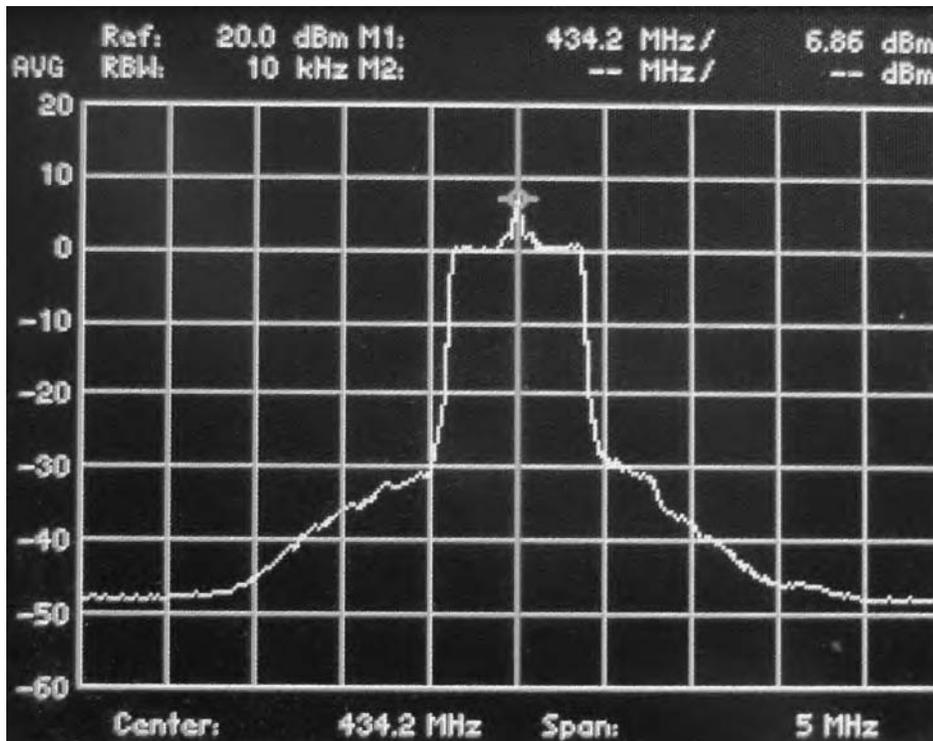


Figure 4 – 50 Watt Power Amplifier RF Output (1 MHz channel)

The receiver is optimized for use over long paths with resultant low signal-to-noise ratios and significant levels of multi-path spread. It uses a soft-decision Viterbi decoder to minimize the SNR requirements plus an outer burst error-correcting code in case the Viterbi decoder fails during deep fades. When a Viterbi decoder fails it tends to generate bursts of errors so a rate-3/4 Berlekamp-Preparata outer code is used [2]. This code is optimal for phased burst error correction and 16-way interleaving is added to increase the length of correctable bursts. The two layers of ECC make the user data rate $\frac{1}{2}$ of the raw data rate. However, the raw data rate in a 20 kHz channel is 38,400 bps compared to 9,600 bps for FSK modems so the user data rate is doubled and the reliability is increased at the same time.

The hardware and software are configurable so 64 to 224 subcarriers can be used with 31.25 to 3906.25 Hz subcarrier spacing. This allows the modem to be configured for use over multiple 2.7 to 1000 kHz wide channels. A guard interval of $\frac{1}{4}$ symbol period allows up to 64 microseconds of multipath spread at a 900 kbps data rate for UHF operation in multiple 1 MHz channels over long paths. HF operation is even possible as up to 8 milliseconds of multipath spread can be tolerated at 8,400 bps in an 8 kHz wide channel.

Multiple Channel MAC

The FCC limits the emission bandwidth for data transmission between 50 and 450 MHz to 20-100 kHz. However, a station can receive on multiple channels simultaneously and transmit on multiple channels sequentially. This turns out to be advantageous in wireless mesh networks where the use of a single channel causes loss of efficiency due to contention and the blocking of multiple potential transmitters by the single transmitter using the channel.

The DCP-6 has been programmed with a multi-channel MAC protocol similar to AACA-SDT [3]. It uses a common control channel and multiple data channels as shown in figure 5. Transceiver A is dedicated to the fixed-frequency control channel while transceiver B can be tuned to any of the data channels.

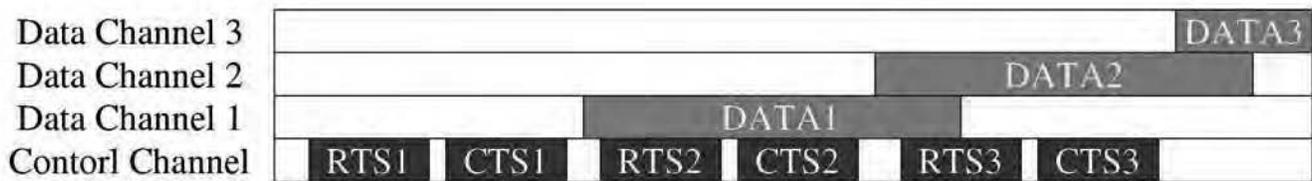


Figure 5 – Use of Control Channel for Rendezvous on Multiple Data Channels

This MAC protocol operates similarly to IEEE 802.11 DCF. The sending station transmits a RTS packet with the desired channel number and the intended receiver returns a CTS packet if the channel is free or a BSY packet (indicating an alternate channel) if that channel is busy. Each packet contains an estimate of the transmission time for the data packet(s). Transceiver B in each station then tunes to the agreed upon data channel for the actual data transfer. All stations monitor the RTS, CTS and BSY packets from neighbors and each maintains a table indicating which channels are reserved by which neighbors and for how long. The control channel operates in a contention mode but the data channels are contention free.

Efficient Broadcasting

Some amateur-radio activity is a point-to-point exchange between two people. However it is also common to have a one to many exchange for nets or multi-person QSOs. In the past, packet radio networks have been designed for point-to-point communication (unicast transmission) but were inefficient at the dissemination of information to multiple recipients (multicasting to a group or broadcasting to all). One method used was simple flooding where each station retransmitted the packets it received. A slight optimization was provided by duplicate detection so that each packet was retransmitted only once. However this still results in broadcast storms when there are multiple stations in range of each other.

Distributed algorithms were developed a decade ago to permit the selection of a minimal set of relay stations that still ensured complete coverage of all stations in the network [4]. Source multi-point relays (S-MPR) provide a good solution for amateur networks as calculations may be done locally on each station, requiring knowledge only of immediate neighbors. S-MPR is an algorithm that can guarantee minimal hop paths and provide different relay sets for different source nodes [5]. Multiple relay sets distributes traffic to ease network congestion.

I've implemented a protocol derived from an Internet draft by replacing IP addresses with MAC addresses [6]. Each node periodically sends a hello packet with a list of known neighbors and the neighbors selected as relays. Receiving nodes update tables of 1-hop and 2-hop neighbors and select the most efficient subset of 1-hop neighbors to act as relays to the 2-hop neighbors.

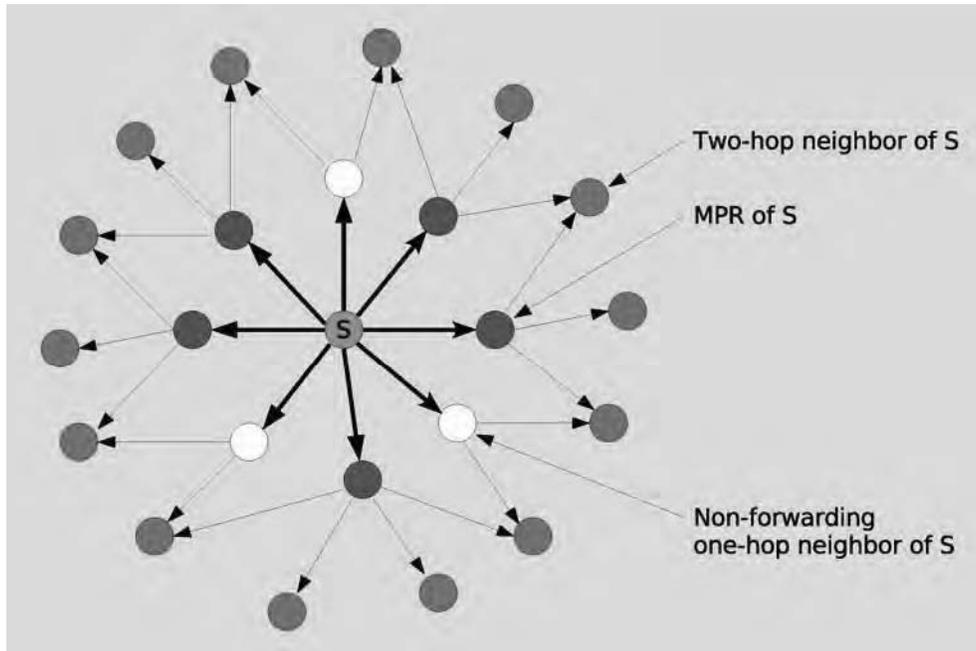


Figure 6 – Source Multipoint Relays (black nodes)

Multicast Routing

The set of multipoint relays provides an efficient broadcast mechanism, but we often want to communicate only with a subset of the available stations. This can be done by giving the desired group of nodes a multicast address and selecting a subset of the relays to forward packets among that group as shown in figure 7. Members of the forwarding group (FG) recognize the address and forward those data packets. The On-Demand Multicast Routing Protocol (ODMRP) [7] was originally developed to handle multicast routing on the internet but generates a lot of traffic as it uses a simple flooding algorithm. It can be extended to use MPR [8] and works in two phases as shown in figure 8.

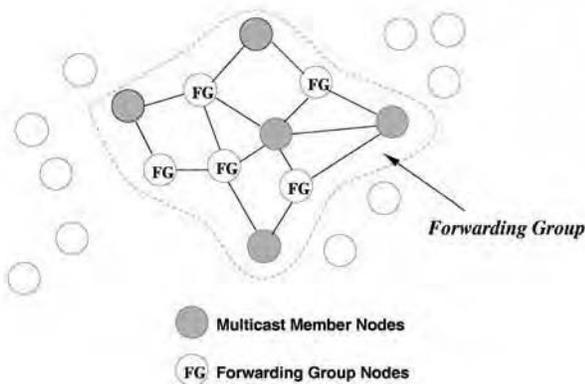


Figure 7 – Forwarding Group

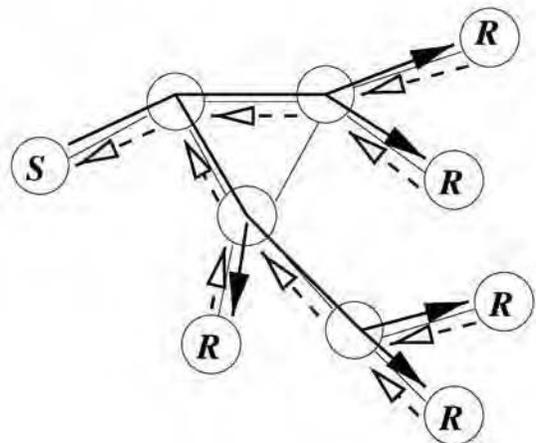


Figure 8 – ODMRP-MPR

Senders periodically broadcast a route request (solid arrows) to all nodes over the control channel. Receivers that wish to join the group unicast replies (dotted arrows) to the source nodes over the control channel. Intermediate nodes along the path to the sender store the multicast address and start relaying multicast data packets on any data channel that is available in their area of the network. When senders or receivers leave the group, the information in the intermediate nodes times out and is deleted.

Unicast Routing

When point-to-point communication is desired, a path can be set up between two specific nodes directly or through intermediate nodes. The Ad-Hoc On-Demand Distance Vector Protocol [9] was developed for that purpose on the Internet and adapted to layer-2 relaying in WiFi networks by IEEE 802.11s. AODV has flooding problems similar to ODMRP but can also be adapted to use MPR [10]. The protocol has request and reply phases that occur when a packet destined for a new address is detected at the sending node. Figure 9 shows the path of the routing request (RREQ) broadcast by the source and the routing reply (RREP) unicast by the destination. Both are transferred on the control channel.

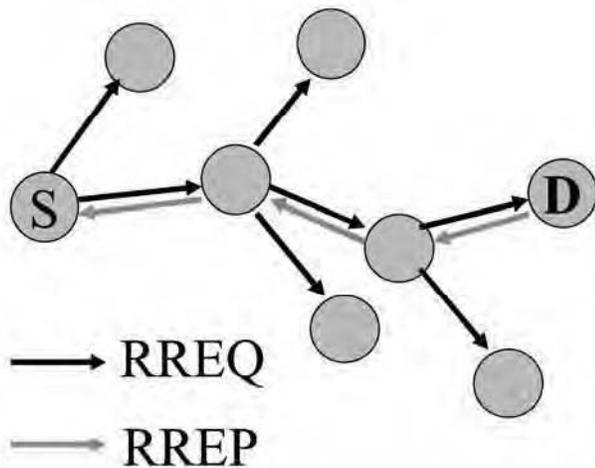


Figure 9 – AODV Route Setup

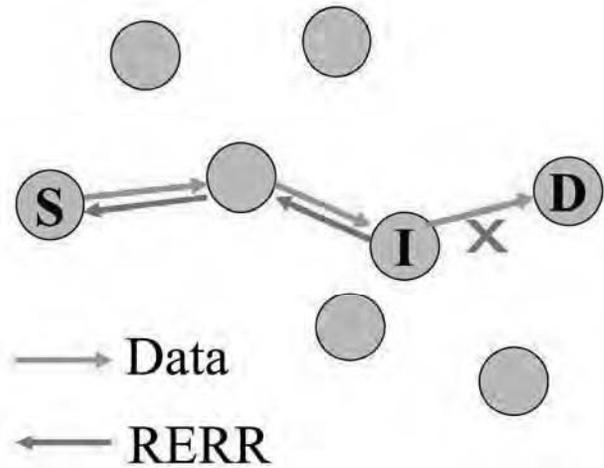


Figure 10 – AODV Route Error

The nodes forwarding the RREQ build up a path to the source by creating routing table entries for the source address with the address of the previous node as the next hop. When the RREP travels from the destination node to the source node, forwarding nodes create routing table entries for the destination address. Routing table entries at nodes along unused paths expire and are deleted. Packets and routing entries contain sequence numbers and path lengths so that the shortest path is always selected. If a node becomes unreachable by moving out of range, the previous node may send a routing error packet (RERR) to notify the source node.

Since AODV and ODMRP are similar, they can be combined into one protocol in order to minimize traffic on the control channel. I've named this the Advanced Wireless Mesh Protocol (AWMP). RREQ packets now contain a list of active multicast group addresses and a list of unicast destination addresses that do not yet have routes from the node originating the request. The RREP packets may contain either a unicast or multicast address so that the intermediate nodes can create either a routing table entry or a forwarding group table entry.

External Interface

AWMP nodes are programmed to look like an Ethernet switch or layer-2 bridge. Each maintains tables of “zero-hop” neighbors connected to the Ethernet ports on each AWMP node. These are the MAC addresses of attached personal computers, routers or other devices. Unicast addresses are detected by monitoring the source addresses of Ethernet traffic and multicast addresses are collected when they are destinations. The MAC address blocks 3333xxxxxxx and FFFFxxxxxxx are reserved as broadcast addresses to support IPv6 and IPv4 routers.

AWMP provides transparency by using data packets that contain 4 addresses – transmit and receive addresses for the AWMP nodes relaying the data packets and source and destination addresses for the attached Ethernet nodes. This bridging mechanism supports existing Internet applications and allows new amateur radio applications to be built using the standard socket interfaces. Most existing routers and firewalls should also be usable with AWMP.

Conclusion

The basic OFDM modem was tested successfully several years ago over 1-10 mile paths. The protocols described in this document have been implemented in assembly language on the CPU16F soft processor in the FPGA. I've tested the new multi-channel MAC among several DCP-6 boards with channel outages simulated by a software process in each board tweaking the channel tables. The protocol implementation performs correctly and negotiates alternate channels without losing data.

The S-MPR implementation and individual AODV and ODMRP implementations have been tested with simulated routing packets injected into the transmit and receive queues by test programs running on the DCP-6. The software merging AODV and ODMRP into AWMP has just been completed and needs testing. Between now and the DCC meeting I should be able to publish this new protocol and do some on-the-air testing.

The AWMP protocol implemented on the DCP-6 FPGA-based SDR should provide a faster, more robust and more flexible data communication on the amateur VHF and UHF bands. It can be used to construct wide-area ad-hoc data networks or even for OFDM-based DATV using IPTV. The existing 1 MHz maximum channel width could easily be increased to 2 or 5 MHz in the future.

I'd like feedback from ARRL and TAPR members on where this technology may be useful. The DCP-6 and associated analog hardware generates and receives RF on the 10-meter band and can be used with VHF and 70-cm UHF transverters. Another approach is a 2-meter version for use with microwave transverters. What would be most useful for ARRL and TAPR members?

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