ABSTRACT

Central to this paper is the use of electronically-steered directional antennas with COTS radio technology to increase performance. In this paper, we describe a multi-sector wireless architecture using several such radios/antennas in a complete system. We discuss networking issues and solutions that arise due to this architecture including link discovery, signal tracking, handover, and the coordination of these between nodes. We also introduce the concept of using a “gateway alias” which provides transparent routing by allowing multiple radios to appear as a single node. The system has been implemented using high gain, switched-beam directional antennas and tested in an operational environment. Results and future direction are discussed.

MOTIVATION

Large divides exist amongst commercial off-the-shelf (COTS), military, and carrier-grade radios. The major areas in which they differ include cost, robustness, and ability to handle several mobile users at long distances. The need to bridge these gaps and enable low-cost, high throughput, line-of-sight (LOS) communications is obvious: the ever-increasing amount and size of intelligence, surveillance, and reconnaissance data; satellite vulnerabilities; and increasing coalition communications to name a few.

Electronically-steerable directional antennas can help boost COTS radio performance to the point where they become useful in military applications. The increased gain of using directional over omni-directional antennas can increase range and decrease probability of interception while electronic steering and appropriate multiple access can support multiple users in different directions.

Controlling these directional antennas and receiving feedback on the link state requires specialized software that is able to control both the antenna and the radio. This interaction with the radio is further complicated when supporting mobility, now that pointing direction is important. A final addition to the software is to control and coordinate amongst several radios on a single platform. As will be described below, a multiple radio architecture provides many benefits despite the additional complexity in software and networking.

The primary sponsors for the work surrounding this paper are the Space and Naval Warfare (SPAWAR) Systems Center Pacific (SSC Pacific) and the Coalition group at the Office of the Chief of Naval Operations (OPNAV). The former has funded internal research and development to address networking issues in directional, mobile ad hoc networks (MANETs). The latter is interested in the rapid transition of such technologies to the Fleet and its coalition partners. In pursuit of that goal, many of the solutions that follow were used in the “Spatially Aware Wireless Networks” (SPAWN) project in the recent Trident Warrior 2008 (TW08) demonstration at sea. The initial paper on SPAWN was presented at MILCOM 2007 [1].

LINK DISCOVERY

The use of directional antennas makes the issue of link discovery more difficult since both sides must have their beams pointed directly at each other at the same time to achieve the optimal signal strength. Several complex algorithms have been developed to optimize link discovery in directional networks [2], [3], [4]. However, implementation of these algorithms depends on having synchronized timing of the transmit and receive functions of the radio and is therefore difficult using most COTS radios that are available today. For example, many radios are carrier sense multiple access (CSMA) and so have uncoordinated transmit and receive times.

For most COTS radios, link discovery simply involves correctly pointing the antenna beams long enough for the radios to complete their association process. Usually this is one Beacon Interval (typically 500ms) plus association time (tens of milliseconds). Therefore, at the very least, the network node must dwell on each directional beam position for this duration of time. The multi-radio architecture discussed below can improve link discovery
time by a factor equal to the number of sectors, since each of the sectors is capable of independently and concurrently scanning for a link within its coverage area.

During link discovery, if the nodes are far apart in distance and the signal to noise ratio (SNR) is low, then the beams of each node must be pointed directly at each other in order to establish a link. However, if the nodes are relatively close and the SNR is high, then it is possible for the radios to link up on non-optimal beams (i.e. the sidelobes of that beam). This further decreases the search time since the truly optimal pointing direction on each node can be assumed to be close. Thus, when – through querying the radio – the control software detects that a link has been found, it should begin sampling the signal strength of adjacent directions or beams of the directional antenna to determine if a stronger link is possible. During this link optimization process care must be taken not to break the link. Synchronization is required so that both sides do not change pointing directions at the same time and thereby corrupt the signal strength readings or, worse, lose the link.

In situations where SNR is low, we found that it is possible for some COTS radios to maintain a “link up” status without actually being able to pass data. This complicates synchronization during link discovery since the two controllers cannot communicate at the application layer. Under these circumstances, one controller is pre-programmed to maintain its beam pointing direction for a long time period, say 10 seconds, after initial “link up.” The controller on the other node is free to begin sampling adjacent beams without the risk of the other side switching at the same time and corrupting the measurement. In order to maintain the link in a low SNR regime, the controller should perform fast samples (~50ms dwell times) of adjacent beams, then switch the antenna back to its original or “home” beam for the remainder of the one second period so as not to miss any beacons. If it finds a beam producing a higher SNR, it should choose that as its best or “home” beam and continue sampling. At the end of this first round, the controllers should then switch roles so that both nodes have an opportunity to optimize the link at their end.

This slow sampling rate for synchronization is necessary to prevent the link from breaking. If the initial SNR is high enough to pass data, then the two controllers can communicate to employ a more advanced synchronization technique. The SNR required for data passing is highly dependent on the radios and their configuration. With the Proxim Tsunami MP.11 radios that were used in TW08, we found that the minimum SNR to be able to pass TCP data reliably is 11dB at 5.8GHz with a 10MHz channel bandwidth setting.

**TRACKING**

Much of the literature regarding MANETs and especially those using directional antennas, focuses on the link – or with multiple nodes, “network” – discovery problem. The implicit assumption, then, is that tracking against mobility is handled by either sending location and heading data amongst all nodes or by rerunning the link discovery algorithm. Two major problems with the first solution are its dependence on unobstructed line-of-sight links and possibly vulnerable resources (i.e. GPS) as well as the load on the network. The second solution is important to discovering changes in the network (e.g. entering/exiting nodes) and should be rerun at somewhat long time intervals. However, link discovery is necessarily complex and time consuming and should be avoided for simple tracking purposes.

Instead, a better solution is to constantly run a simpler tracking algorithm on the controllers. With the sole purpose of maintaining and optimizing preexisting links, this software can be as simple as sending switch beam commands, sampling signal strength, and comparing those values to select the beam resulting in the highest SNR. The two most important issues for this type of tracking are 1) How long can you stay off the current, working beam without breaking the link? and 2) How long must you dwell on the sampled beam to get an adequate power reading? Using the physical simulation system described in [5], we found that 50ms was sufficient to get an accurate power reading, as long as some data was being pushed across the link. This is because signal strength as reported by 802.11 radios is calculated upon the receipt of a packet by the data link layer. These values are averaged over time, so receiving packets constantly helps ensure that the reported value is up-to-date.

Our initial tracking algorithm was also the most straightforward, and it consisted of the following steps:

1. Sample/store signal strength on current beam.
2. Switch antenna to the next beam to the left.
3. Sample/store signal strength on left beam.
4. Switch antenna to the beam just right of original.
5. Sample/store signal strength on right beam.
6. Update the “current beam” direction to be that which produced the highest signal strength.

This procedure took about 150ms and was repeated every 2-3sec. Though simple and effective, we found during
lab-based limited objective experiments for TW08 that the constant sampling of beams caused a noticeable degradation of performance. This was especially true while testing at low SNR or at the far edges of our antenna array steering. Furthermore, constant tracking assumes that the nodes are constantly moving relative to each other. For many military mobility patterns, for example steaming in formation or driving in convoys, this assumption is unnecessary.

A more fitting solution in the case of infrequent relative node movement is to trigger the tracking algorithm on a drop in signal strength. This change should be significant, beyond a certain threshold that will account for inherent variations in radio-reported signal strength (and probably to include fast fading effects that are averaged by the the radio's calculations). So, when the controller detects that the signal strength has dropped, it assumes the cause is either that the remote node has moved or that the local platform has moved or rotated and so searches for the new optimal beam pointing direction.

THE MULTI-RADIO NODE ARCHITECTURE

At this point, it is necessary to describe and differentiate between two architectures for using directional antennas with COTS radios. The first, and most intuitive, is to use a single radio and replace its omni-directional antenna with a single, directional antenna that can switch or steer to all 360°. This works well if the antenna can be placed in a high, unblocked area. However, since directional antennas need physical area to produce gain, placing them on masts or on top of Humvees may be unacceptable for reasons of wind resistance, camouflage, or blockage of other systems.

A second architecture is to place multiple, smaller directional antennas on the platform. Planar/conformal antennas work well in this setting. One can then use an RF switch to choose amongst the antennas or attach each to its own radio. This latter solution avoids the loss in having long RF cable runs from antenna to antenna as well as a multi-port switch, but it requires additional software to manage the multiple radios. The low cost of COTS radios makes this sort of architecture feasible, and several groups besides the authors have fielded such systems. *For example, Mobilisa also uses this architecture in their Floating Area Network (FAN) project, demonstrated at TW08.

The use of both directional antennas and multiple radios on a single network node requires an additional set of control software. What has been called a “controller” to this point should now be called a “sector controller” as it monitors and controls the sector defined by a directional antenna and associated radio. The second type of software, which we call the “master controller,” directs the operational state of the system as a whole. The master controller receives status updates from all of the sector controllers and instructs them to perform the proper functions at the correct time. The master controller also acts as a smart router, interfacing with the directly connected network and updating routes according to which radios have links. This essentially allows the multiple radios to appear a single network node.

HANDOVER

An interesting development from the above architecture is the need for sector-to-sector handover. The cellular phone industry has had a similar concept for many years now: the “handover” of a link from sector-to-sector and base station-to-base station as a mobile user drives across the city. For the wireless communications system described in this paper, and especially MANETs, the situation becomes more complicated in that each node is mobile and must be able to handover amongst its own antenna-plus-radio sectors. So, handover is “intra-node” rather than being solely an issue of the backbone or infrastructure of the network.

For the SPAWN system tested at TW08, handover is enabled by allowing the radios to perform their programmed roaming procedure, detecting link status changes (up/down), and modifying the routing tables accordingly. This is done using the concept of a “gateway alias.” The gateway alias is an IP address that is applied to every interface on the master controller that is connected to a radio. The routing table changes needed after a handover, then, are to simply replace Ethernet device numbers in the static route to the network on the remote node. This method enables the change to be transparent to the node on the other end of the link. Reassigning the IP address requires a flapping of the interface, which can disrupt both data flow and communication between the master and sector controllers.

The Proxim Tsunami radios that were used in TW08 operate in infrastructure mode: either as base stations or subscribers. In some ways, the predetermined roles of “base station” and “subscriber” complicate the handover process as multiple subscribers could connect to a single...
base station, but not vice versa. A diagram and description of handover within a base station node are below.

In the figure above, Ship 2 is the base station node and starts off with a link on its aperture 4 antenna (sector 4). As Ship 2 steams past Ship 1, the geometry changes so that Ship 2's aperture 1 antenna has the most direct look at Ship 1. Ship 1's radio (a subscriber) gradually notices the signal strength of the link declining and begins roaming once it drops past a certain threshold. It will roam to the radio connected to Ship 2's aperture 1. The controller for sector 1 on Ship 2 detects the new link status and relays it to the master controller which then begins routing packets over device eth1. The gateway for Ship 2 must be 192.168.0.254 since that is where Ship 1 sends its packets: the gateway alias. The change to the routing table is

192.168.1.128/26 via 192.168.0.253 dev eth4 becomes...
192.168.1.128/26 via 192.168.0.253 dev eth1

Handover across two subscriber radios is much simpler since two subscriber radios can be concurrently linked up with a single base station. In this situation, the master controller on the subscriber side (e.g. Ship 1) knows there are two links, and it simply chooses to route packets over the interface with the highest signal strength.

**COMMUNICATING WITH THE RADIO**

There are several important parameters that a radio must be able to provide if it is to use the multi-radio architecture and these network solutions. The most important of these are signal strength, link state, and roaming parameters. For COTS radios there may be several ways of obtaining these parameters using outside applications. The most prominent and widely available is with the Simple Network Management Protocol (SNMP). For example, SNMP is used by SPAWN to communicate with the Proxim Tsunami radios: querying the state of the sector and issuing commands. As an alternative, many radios provide command line applications which could be used to obtain this information programmatically. A third possibility exists for 802.11 radios that are controlled with open source drivers such as MadWifi. Open source drivers may provide access to an abundance of low level device state information.

**CURRENT IMPLEMENTATION AND RESULTS**

Some details of our current implementation have already been described. SPAWN technology was used to outfit two US Navy ships for the TW08 exercises this past June. Full 360° coverage was achieved by using four Proxim Tsunami MP.11 radios, each tied to an electronically-steerable directional antenna able to steer across 90° with approximately 12°-wide beams. The sector controller software ran on low power single board computers running Linux, and the master controller software ran on a ruggedized laptop, also with Linux. Four additional Ethernet ports were added to the laptop using USB-to-Ethernet adapters and a 4-port USB hub. This effectively turned the laptop into a custom 5-port router.

Handover ran as described above, and the tracking algorithm that we used was based on the reactive (versus
timed) criteria for sampling neighboring beams. Regarding this last point, we found that large fading effects, such as those caused by reflections over water, defeat the steadiness of the reactive algorithm. This is especially true when the two nodes are separated by a short (1 – 5 miles) distance and the antennas are placed high off of the water level (~100 feet). The fading problem was exacerbated by the fact that the ships were rocking in the seas, effectively shifting the deep fade regions back and forth in distance. These phenomena were verified with SSC Pacific's Advanced Refractive Effects Prediction System (AREPS) software [8].

Despite these setbacks, we were able to pass multiple video feeds at a distance of 12 nautical miles, and our peak TCP throughput was 5Mbps.

CONCLUSIONS AND FUTURE WORK

In this paper we described several network solutions to help develop COTS radio-based systems to the point where they can function in an operational military environment. As this requires the use of directional antennas, the additional issues of a coordinated link discovery and tracking are raised. Furthermore, in order to avoid long and lossy RF cable runs and to reduce mast/topside crowding, multi-radio architectures promise to become more and more prevalent, especially considering the low cost nature of COTS radios. Methods for enacting “intra-node” or sector-to-sector handover were discussed, including the use of a gateway alias to simplify routing.

The SPAWN system described here was recently demonstrated in an operational environment using modified 802.11a radios. The system demonstrated major improvements in distance, data rates, and cost due to this technology. In the near future, we are interested in working with time division multiple access (TDMA) radios to allow for sub-frame switching. This would enable communication to multiple remote users within a single sector with quickly switching beams to service all nodes in the sector. Possibilities include several forthcoming 802.16e radios and the SeaLancet radio [9].

REFERENCES