TACTICAL MOBILE MESH NETWORK SYSTEM DESIGN

Adam Blair[1], Thomas Brown[1], Keith M. Chugg[1,2], Mark Johnson[1]

[1] TrellisWare Technologies, Inc.
16516 Via Esprillo, Suite 300
San Diego, CA 92127–1708
{ablair,tbrown,kchugg,mjohnson}
@trellisware.com

[2] Communication Sciences Institute
Ming Hsieh Dept. of Electrical Engineering
University of Southern California
Los Angeles, CA, 90089-2565
{chugg}@usc.edu

Abstract— **Tactical mobile mesh systems are wireless communication networks characterized by: harsh propagation channels and interference, frequent and rapid changes in the network topology, the requirement for very robust, low latency multimedia information decimation, and no centralized network control. In this paper we describe a technology testbed designed to address these challenges. The testbed is based on advanced waveform technologies, modern digital likelihood receiver processing, and robust ad-hoc networking strategies. A technology testbed was assembled to evaluate the cumulative benefits of this integrated system design. Field tests are presented demonstrating low-latency voice and multimedia IP traffic over multiple hop, cooperative routes.**

I. INTRODUCTION

Tactical mobile mesh (TMM) systems are wireless communication networks characterized by: harsh propagation channels and interference, frequent and rapid changes in the network topology, the requirement for very robust, low latency multimedia information decimation, and no centralized network control. These features distinguish such networks from mesh networks (stable network topology), sensor networks (low data rate, delay tolerant), and ad-hoc networks (relatively benign RF environments).

The design challenges associated with this mobile mesh network are significant and account for the limited success of proposed systems. For example, modification of WiFi networks to remove centralized control has limited potential due to PHY and MAC layer overhead and optimization for static channels with stable, centralized network topologies. This motivates cross-layer design approaches. In this paper we describe a cross-layer approach to the design of tactical mobile mesh network design that integrates PHY and MAC processing with a focus on robustness to highly dynamic network topology and physical layer channel conditions. We describe a technology testbed that incorporates these design principles and provide results of preliminary field testing.

The proposed design is based on a very robust waveform technology and the associated receiver signal processing. In particular, the system uses advanced constant envelope waveform technology for robustness to non-linearities (amplifiers, limiters, etc.), frequency hopping, modern error correction, and adaptive iterative detection receiver processing. These components allow for exceptional robustness and range at the link level by capitalizing on multiple sources of diversity. In addition, these PHY level features are utilized to implement cooperative diversity in transmission through the network; therefore allowing for multiple route diversity. This cooperative diversity and decode-and-forward processing form a tight coupling between the PHY and MAC.

At the MAC and above, a Dynamic Network Architecture (DNA) design is employed. This approach has several potential advantages. These advantages arise from the fact that DNA design has truly distributed control that is agnostic to the current network topology. This enables, for example, cooperation between nodes without handshaking or team-forming protocols. These features also allow nodes to join the network seamlessly with low-latency or, equivalently, for multiple networks to merge or split as the mission and network topology dictate.

A technology testbed was assembled to evaluate the cumulative benefits of this integrated system design. The testbed is capable of relaying over up to nine nodes and delivers multiple channels of low-latency, cellular quality, push-to-talk voice over multiple hops. In addition, IP traffic, including streaming audio and video are supported over multiple hop, cooperative routes. This mobile mesh testbed has been operated in various environments and some of these test results are summarized.

The testbed objectives are summarized in Section II. An overview of the key technologies used in the testbed are summarized in Section III. The hardware configuration used for testbed nodes is summarized in Section IV and the results of selected tests are described in Section V.

II. Testbed Objectives

TrellisWare has developed and implemented a number of physical layer technologies that enable very robust and efficient point-to-point communication in harsh propagation environments. A common theme in this development has been to leverage Moore's law to enable the latest research results in communication theory to be implemented on standard digital hardware platforms (*e.g.,* field programmable gate arrays (FPGAs)). The resulting waveform technologies, such as instantiated in Soldier Radio Waveform (SRW), have proven to provide a valuable, robust radio link in time-varying, multipath fading environments.

Many tactical scenarios, however, demand a method for robust, fast dissemination of information among a loosely organized group of users. Meeting this demand by retrofitting existing systems to operate in a mobile mesh fashion is proving to be difficult. One hypothesis is that these difficulties are primarily due to the lack of design integration between the point-to-point waveform capabilities and the ad-hoc routing strategies.

The objective of the TMM testbed is therefore to investigate the extent to which our advanced physical layer designs, coupled with a simple, robust ad-hoc routing scheme can address the demands of TMM scenarios.

III. Overview of Core Technologies

The key physical layer advances underlying TrellisWare's PHY processing and TrellisWare's robust ad-hoc networking strategy are described briefly in the next two subsections, respectively.

A. Modern Digital Likelihood Processing

Since its inception in the year 2000, TrellisWare has been implementing advanced receiver processing algorithms and leveraging these capabilities by designing more efficient and robust waveform technologies. We first summarize receiver processing technologies and then describe complementary signal design concepts.

1) Receiver Processing: The receiver processing algorithms are based on Digital Likelihood Processing [1][1] which is the application of Bayesian decision theory (*e.g.,* see [2], [3]) to complex data decision and estimation problems. The methods can be categorized into two types according to the objective. First, when channel parameters change quickly or are generally unknown, as in the case of highly-mobile platforms, one may desire to *jointly estimate parameters and make data decisions*. Second, when a system is comprised of a number of subsystems (*e.g.,* an error correction code and an intersymbol interference (ISI) channel), one may want to perform *iterative detection* (*e.g.,* iterative decoding and equalization).

In the area of joint estimation and data detection, Per-Survivor Processing (PSP) [4] is a method to incorporate parameter estimation into a data-detection algorithm based on the Viterbi algorithm [5]. By eliminating the delay in the data-directed estimation loop used in conventional methods, PSP allows for the tracking of higher parameter dynamics. PSP can also be interpreted as a greedy approximation to the optimal, yet impractically complex, processing [6]. Like the Viterbi algorithm, PSP yields hard decisions on the data sequence whereas often times soft decisions are sought. With perfect channel knowledge, the forward-backward algorithm (FBA) [7], [8], is the extension of the VA that provides optimal soft decision information. Specifically, the FBA can be used to implement a so-called soft-in/soft-out (SISO) processor that takes in soft decision information (soft-in) and updates it to provide updated soft decisions (soft-out). Analogous to PSP, adaptive SISO algorithms can be viewed as extensions of the FBA that combine parameter estimation and tracking with the associated trellis processing. Adaptive SISO algorithms can also be seen as practical approximations to the prohibitively complex, optimal processing [9].

Iterative detection is the generalization of the turbo decoding algorithm and can be applied to systems that comprise a concatenation of simpler subsystems or are modeled as such. Given a model for this partitioning, a standard set of message-passing rules exists to update soft decision on the system variables of interest [8]. The power of iterative detection methods is that they approximate the optimal joint processing of the global system by repeatedly performing SISO processing of simpler (local) subsystems. The modern view of this is based on graphical models. If a given system is modeled using a cycle-free graph, then the message-passing rules are optimal. Graphical models of complex, concatenated systems will, however, typically contain cycles. For such cyclic graphs, the message-passing is suboptimal but is a very good approximation to the optimal processing when the cycle structure is well-designed [10]. In practice one controls the cycle structure through the design of interleavers used in the system.

[1]References in this paper are not exhaustive and are intended to provide context for the technologies underlying the testbed.

Note that the notions of iterative detection and joint estimation and data detection are complementary. For example, using an adaptive SISO in an iterative detection algorithm will result in joint estimation and data inference at each iteration – *i.e.,* the channel parameters are re-estimated as the soft decisions become more reliable. Algorithms that combine joint parameter estimation and iterative detection are referred as Adaptive Iterative Detection (AID) algorithms [9], [8].

Finally, note that the aspects described above can be combined if required by a particular application. For example, one could utilize an adaptive, reduced-state SISO in an iterative receiver. The best algorithm for a particular application is the one that yields the desired performance with the lowest implementation complexity. Designing such an algorithm for a particular scenario, particularly with implementation architectures considered, is more art than science and experience is invaluable for a timely design.

2) Enabled Signal Designs: Utilizing the advanced receiver processing methods described above enables the use of waveform technologies with lower overhead for training, higher spectral efficiency, and greater robustness to hardware imperfections and channel distortions. An obvious example is the use of modern or turbo-like codes [11] which can be decoded in practice by using iterative decoding.

Modern codes typically provide 3-8 dB of additional coding gain relative to classical coding approaches. One challenge associated with modern codes is that most of designs in the literature are optimized for a particular rate, block size, and target error probability. In highly dynamic environments with various traffic types, a codec that supports a wide range of code rates and block sizes, with good performance in all modes, is desired. TrellisWare developed a class of modern codes, called Systematic with Serially Concatenated Parity (S-SCP) codes [12], [13] with these characteristics. One type of S-SCP code is based on simple two-state encoders and can be viewed as a Low Density Parity Check (LDPC) code. TrellisWare has developed very low complexity codec hardware for this Flexible LDPC (F-LDPC) [12], [13].

TrellisWare has also developed advanced continuous phase modulation (CPM) waveform technologies for robust terrestrial modems. These designs utilize joint equalization, demodulation, and decoding using the receiver processing described above. For example, an adaptive SISO was designed to jointly perform CPM demodulation, equalization, and multipath channel tracking in [14]. In concert with decoding an error correction code, this AID-based receiver demonstrated significant performance advantages over conventional approaches. TrellisWare designed a hardware-prototype of a similar CPM system with frequency hopping as reported in [15]. This led a number of related designs [16], [17], each optimized for a specific operational scenario, including the Soldier Radio Waveform (SRW).

TrellisWare also developed another PHY advance to enable simple, robust cooperative communications. This method is based on dithering the carrier phase at the transmitter to induce time-varying interference patterns at the intended receiver. Modern error correction codes, such as the F-LDPC, are then used to code over these time-varying patterns. This method provides diversity against the worst case (destructive) interference pattern at the receiver that could occur with no coordination and without a dithering technique. Simplified versions of this method allow for cooperation with only rough time synchronization among transmitting radios. Specifically, neither the transmitters nor the receiver need to know the number of transmitters or any of the individual channel characteristics; the receiver can simply receive and process the composite signal as if it came from a single node. Despite the simplicity of this approach, the analysis performed in [18] shows that it is quite effective relative to more ideal and less practical cooperative communication methods.

B. Dynamic Network Architecture

In this section we summarize a simple, robust, autonomous method for dissemination of information in a tactical mobile mesh system. This design is based on a robust physical layer capable of providing node communications in severe multipath environments. As an example, the anticipated environment would involve nodes that are all in a dense urban environment and connectivity is desired throughout the network as nodes traverse structures in this environment. In contrast to cellular communications, all of the transmitters are typically in the dense scattering environment (*i.e.,* as opposed to cellular base-stations). This fact, combined with mobility, requires a PHY waveform technology that can maintain a link in the presence of abrupt changes in channel conditions which may occur, for example, as nodes round corners or exit basements in an urban grid. The frequency-hopped CPM signals with flexible modern coding as described above provide a good solution to address these demands. Specifically, these modulations are robust to amplifier nonlinearities, RF impairments, dynamic, frequency selective fading and also do not require precise gain control. Thus, such waveform technologies, along with the ability to perform cooperative communication as described above is assumed through the following discussion.

A multi-hop, cooperative relay system is considered. The basic operation is that when a message is initiated by a node, it is relayed outward from that node by subsequently larger rings of nodes until the information has been disseminated throughout the network. Relaying is done by a decode-and-forward approach. Node connectivity is determined by the ability to successfully decode a message as determined by an error detection code used on top of the modern code. The network operation is autonomous in the sense that as the connectivity of nodes changes, the basic node operations do not change. Channels are reused spatially and this is accomplished automatically as connectivity and the number of nodes change. This also allows nodes to enter and exit the network rapidly (*i.e.,* without a registration process). This includes the possibility of splitting a network into two networks or the reverse operation of combining two networks into one.

This autonomous broadcast strategy can be accomplished by a method of multiple access; we will describe a time division multiple access (TDMA) based approach. This requires slot-level synchronization throughout the network which can be accomplished using low overhead pilot signaling. Consider a 3-slot TDMA frame format with slots labeled as A, B, and C. Suppose a given node initiates a transmission on slot A. All nodes that successfully decode this are, by definition, one hop away from the source node (these are the blue nodes in Fig. 1). These nodes then transmit the same information on slot B, thus relaying to the nodes that are two hops from the source (green nodes in Fig. 1). The nodes that are two hops from the source (green nodes), then transmit the same information on slot C. Nodes that are 3 hops away from the source (red nodes in Fig. 1) receive this information and then transmit it on slot A of the next TDMA frame. In this way, the message propagates outward from the source. To prevent the relay transmissions from propagating back inward toward the source, each node repeats what it receives or originates only once and on the next TDMA slot. For example, the source will receive the transmission on slot B from the nodes one hop away, but it will not retransmit it. Similarly, the nodes one hop from the source will not transmit the relays heard on the slot C from the nodes 2 hops from the source.

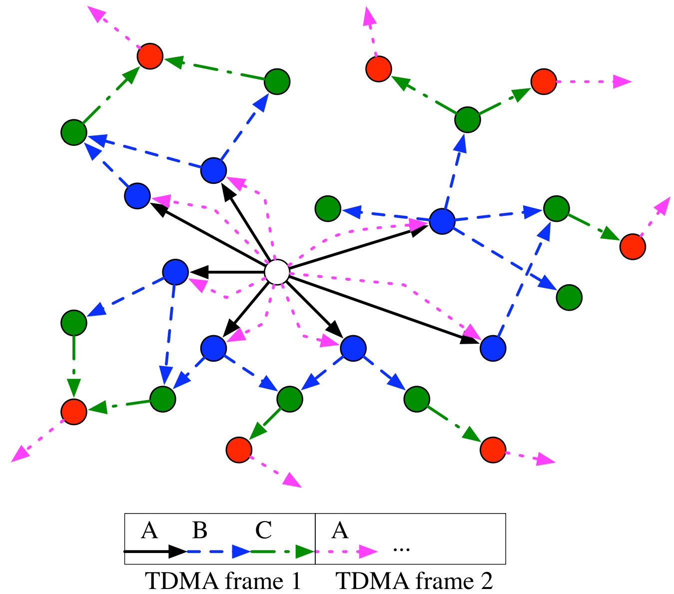

Fig. 1. Autonomous relay example.

Note that because all nodes transmit what they receive, cooperative communications will occur. For example, a node two hops from the source may receive transmissions on slot B from multiple nodes that are one hop from the source. This cooperation is achieved automatically with no knowledge of the various propagation channels or relay coordination. Note that this may allow for successful relaying of a message when none of the individual links are strong enough to provide connectivity on their own.

Also of note is the fact that, assuming the connectivity is fixed for a TDMA frame, the nodes that are one hop away from the source will not receive the transmission on slot A by the nodes that are 3 hops away from the source. This is because the nodes 3 hops away, by definition, did not receive transmission on slot B by the nodes that are one hop from the source. Thus, the source is free to transmit again on slot A of this next TDMA slot. In this manner the outward propagation of messages from the source can be pipelined. The resulting reuse efficiency is maximized spatially by the automatic reuse of channels. The 3-slot frame format results in a reduction of throughput by 1/3 that may be viewed as a price to be paid for the completely autonomous operation. Furthermore, with slight modifications, this price can be reduced for links that employee less than 3 hops.

Note that each TDMA slot can itself comprise a robust, frequency-hopped, coded link. Similarly, the basic channelization strategy described could be utilized with other multiple access methods. For scenarios with primarily broadcast traffic the scheme described is desirable. Routing in such a network can be achieved by including an address header in the message and appropriate encryption. For applications where most traffic is from one node to another, more complex variations of the approach described can be used. This would involve, for example, dissemination of some network information to allow for multiple routes to use the same channel resources simultaneously.

The method describe above is robust to merging and splitting of networks as the propagation and physical network topology dictate new network connectivity topology. In the case of merging two networks as method of resolving the different synchronization signals is required.

IV. Testbed Hardware and Capabilities

TrellisWare's tactical mobile mesh testbed architecture is designed based on the waveform and networking technologies described above. The PHY is based on a variant of GMSK with F-LDPC coding. The testbed uses a TDMA scheme with frequency hopping, similar to the example given. Modulator parameters, as well as the carrier frequency, are flexible.

The nodes were designed to accommodate multiple standard data types including multiple voice circuits and IPv4 and IPv6 data including IP streaming video and audio. Through intelligent selection of hardware, standard data I/O's, such as USB and Ethernet, allow the units to be connected to standard commercial application peripherals such as computers, cameras and Ethernet switched communication gateways. This approach provides the greatest overall flexibility.

Transmission of video and IP data is accommodated through dedicated data channels independent of the voice channels, allowing any node to communicate directly with any other node without having to traverse through a command node. Streaming video data is one of the most network-stressing data types due to its high sensitivity to perturbation in latency or channel loss conditions. TrellisWare's DNA design is tuned specifically to handle streaming video over a multi-hop network seamlessly without requiring operator intervention. IPv4 and IPv6 data types are both accommodated in the testbed node I/O architecture. The IP data type, IPv4 versus IPv6, is provided by the host computer connected via USB interface, and the internal I/O processor can accommodate either addressing scheme.

Fig. 2. Testbed node hardware.

Each node in the testbed consists of man-pack unit with omni-directional antennas radiating up to 1 watt peak power (average power utilized on an active voice channel is less than $1/100^{\mathrm{th}}$ watt). Also included are a streaming video source, GPS unit for location tracking, and a laptop computer that provides a real time diagnostic user interface. All of these features were designed to allow a technically capable operator the ability to monitor the operation of the system during its operation. The testbed node unit is shown in Fig. 2.

The hardware consists of three main boards: an RF, digital baseband, and a digital I/O processor. The RF design consists mostly of off the shelf cellular and WiFi parts, simplifying and significantly reducing the cost of the overall design. The digital baseband is hosted on reprogrammable logic, allowing software upgrades. An on-board processor adopted from commercial smart phones provides significant on-board processing power and data handling options. The nodes were designed as a flexible evaluation platform supporting a wide range of deployment scenarios from vehicle to backpack mounting. The interfaces and data sources supported allow for evaluation of voice, video, data, and location tracking of a network of nodes working cooperatively.

V. Field Testing

Test data have been collected in a wide variety of environments that challenge the individual components of the approach as well as the combined approach on the whole. These environments have included open desert, industrial park, dense urban, storm drainage systems and an aircraft carrier. Tests employed from two to eight units, depending on the nature of the test. While test metrics of link quality and network connectivity were maintained, 3 applications were run simultaneously on the network to provide tangible, qualitative evidence as

Application	Latency	Network Outages
PLI	Non-Sensitive	Non-Sensitive
Voice	Highly Sensitive	Mildly Sensitive
Streaming Video	Highly Sensitive	Very Highly Sensitive

TABLE I

SUMMARY OF LATENCY AND OUTAGE SENSITIVITY FOR VARIOUS TRAFFIC TYPES..

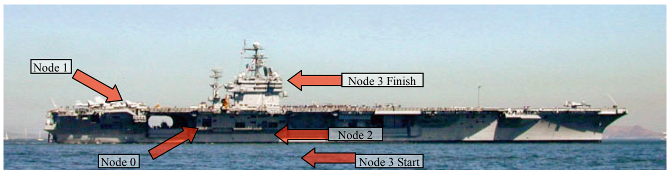

Fig. 3. U.S.S. Midway field test configuration.

to how the network performs. These were position location information (PLI), low-latency voice, and streaming video. Network latency and outages impact each of these data types differently. PLI is robust to all but the worst latency and outages, voice is quite sensitive to latency, but is fairly robust to outages, while streaming video is quite sensitive to latency and extremely sensitive to any outages. This is summarized in Table I.

A. Shipboard: U.S.S. Midway (Aircraft Carrier)

Shipboard is an extremely dense multipath environment. It consists of narrow walkways and wide open areas (in the case of an aircraft carrier hanger deck) where all walls, floors and ceilings are near-perfect reflectors (painted metal). In this harsh an RF environment, it is critical that the physical layer be extremely robust.

Shipboard testing was performed on the U.S.S. Midway, a decommissioned aircraft carrier in the San Diego harbor. The baseline configuration had four nodes as shown in Fig. 3. One node was the video sink and was positioned on the hanger deck (Node 0 in Fig. 3). A second node was on the on the flight deck with no line-of-sight to the video sink (Node 1 in Fig. 3). A third node was two floors below the hanger deck between the hanger deck and the engine room (Node 2 in Fig. 3). Again there was no line of sight between this relay and the video sink. A roaming node (Node 3 in Fig. 3) was used to source video from the engine room (approximately 5 floors below the hanger deck). This roaming node proceeded to walk up from the engine room, through the hanger deck, up a closed elevator to the flight deck, and then up into the bridge (approximately 4 floors above the flight deck). This path was walked without packet error (between video source and sink) and with no perceivable impact to video or voice latency. The switching between the relaying nodes occurred without any impact on the end user ($<$ 10 ms voice latency variation and no packet loss). Throughout all testing, low-latency voice communications were on-going between all nodes involved.

B. Dense Urban: Downtown San Diego

Dense urban environments have always been known to be one of the most challenging RF propagation and ad-hoc networking environments. Ground-based communication systems are forced to deal with tall, tightly-packed, metal buildings that create dense multipath. They also deal with sharp turns that can cause rapid signal variation of 30 dB or more. These test the physical layer processing, but also the networking approach as 30 dB fades can cause rapid outages and require instant re-routing.

The test scenario depicted below consisted of a video/data sink on the hanger deck of the U.S.S. Midway (see Fig. 4). Two nodes were positioned on the flight deck of the Midway on opposite sides, separated by approximately 100 ft. Neither of these two nodes had a direct line-of-sight to the video sink, but one was able to make a direct link none-the-less. The second node on the flight deck had connection to the video sink through the second node on the flight deck. The video/data source in this test was in a vehicle driving through downtown San Diego. It is worth noting here that the nodes on the flight deck had relatively high position, but no direct line-of-sight to the majority of downtown San Diego because of a dense Navy building (Obstruction in Fig. 4). It is also worth noting that the vehicle-mount node was still using the same hardware as the other nodes (1W peak transmitter with omni-directional antenna).

The blue in Fig. 4 shows the range that was covered directly from the hanger deck. Green depicts the area covered through a single relay and red is the area covered by two relays. The rapid re-routing of the network is apparent from “Area 1” (Fig. 4) where the path switches between green and blue very rapidly (note that data points are taken at approximately 1 sec intervals). More rapid re-routing of the network is shown at “Area 2” of Fig. 4, where the path switches rapidly between green and red. An interesting point to highlight here is the diversity gains realized by having two nodes on the flight deck. Although these nodes are relatively close, they are spaced far enough apart to realize diversity gains. With one intermediate node, a voice transmission in Area 2 would sound fragmented. With the two intermediate

Fig. 4. Summary of downtown San Diego field test.

nodes, the voice transmission has imperceptible (though some) packet loss. Approximately one third of transmission in this scenario required multiple hops.

VI. Conclusion

These paper provides a summary of technologies underlying TrellisWare's tactical mobile mesh network testbed and some representative field testing data. The underlying link-level technologies are based on modern error correction coding, robust constant envelope modulations, and adaptive iterative detection receiver processing. These PHY technologies have been coupled with robust, autonomous ad-hoc networking algorithm that allows for reliable decimation of information throughout an ad-hoc network under rapidly changing network topology and propagation characteristics. Key notions utilized include methods for autonomous cooperative relaying and channel reuse. The field test results indicate that there is a synergistic advantage gained by simultaneously implementing robust PHY links and robust routing algorithms that rely on characteristics of the waveform and receiver processing technologies. Further data collection efforts can lead to a better understanding of how each of the concepts discussed in this paper contribute to the overall testbed performance observed.

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