Adaptive link-layer intelligence for enhanced ad hoc networking

James MacLennan, Bill Walburg, Larry Nevins, David Hartup
Nova Engineering, 5 Circle Freeway Drive, Cincinnati, OH, USA 45246-1201

ABSTRACT

Networked radio systems that utilize self-forming, fault tolerant techniques offer needed communication functions for Homeland Security and Law Enforcement agencies. The use of an ad hoc mesh network architecture solves some of the problems inherent to the wireless physical layer such as interferers, multi-path fading, shadowing, and loss of line-of-site. These effects severely limit the performance of current 802.11 wireless network implementations. This paper describes the use of Adaptive Link-layer Intelligence for Enhanced ad hoc Networking. This technology enhances recognition and characterization of sources of wireless channel perturbations and predicts their effects on wireless link quality. Identifying and predicting channel problems at the link level improves dynamic route discovery, circumvents channel disruptions before they cause a link failure, and increases communications reliability and data rate. First Responders, Homeland Security, and Law Enforcement agencies operating in locations lacking infrastructure, such as Urban Search and Rescue (USAR) operations, can benefit from increased communications reliability in highly impaired channels that are typical in disaster response scenarios.

Keywords: Mobile ad hoc network, MANET, Hidden Markov Model, link quality, search and rescue, robot, first responder, communication link, throughput

1. INTRODUCTION

This paper presents a method to recognize and characterize sources of wireless channel perturbations and predict their effect on wireless link quality. The technique uses a novel approach to identify and predict channel problems at the link level and improve dynamic route discovery. This provides increased performance in wireless networks for real-time data streams, such as audio and video.

With the advent of new mobile technologies such as laptops, personal digital assistants, and robots, first responders are eager to deploy a wireless network architecture that is easy to maintain, provides connectivity to the greatest number of nodes and does not create networking bottlenecks. The use of an ad hoc mesh network architecture solves some of the problems inherent to the wireless physical layer such as interferers, multi-path fading, shadowing, and loss of line-of-site. These effects severely limit the performance of current 802.11 wireless network implementations. However, for critical data, such as streaming voice and video, deploying an ad hoc wireless network is not enough. Channel anomalies make link guarantees difficult to provide. This paper demonstrates a technology providing the ability to recognize the type of interference on a wireless channel.

1.1. Mobile Ad hoc Networking

The Internet Engineering Task Force (http://www.ietf.org) has defined a Mobile Ad hoc Network (MANET) as:

> "an autonomous system of mobile routers (and associated hosts) connected by wireless links--the union of which form an arbitrary graph. The routers are free to move randomly and organize themselves arbitrarily; thus, the network's wireless topology may change rapidly and unpredictably. Such a network may operate in a standalone fashion, or may be connected to the larger Internet".

Simply put, a MANET is a wireless mobile network that is self-forming, self-maintained, and self-healing. Nodes stay connected even as the network topology changes.

This paper describes how to improve the performance and reliability of real-time streaming data through a wireless network deployed by first responders. The technique utilizes innovations in detecting and predicting channel phenomena caused by local interferers, shadowing, multi-path fading, unidirectional links, and other channel effects.

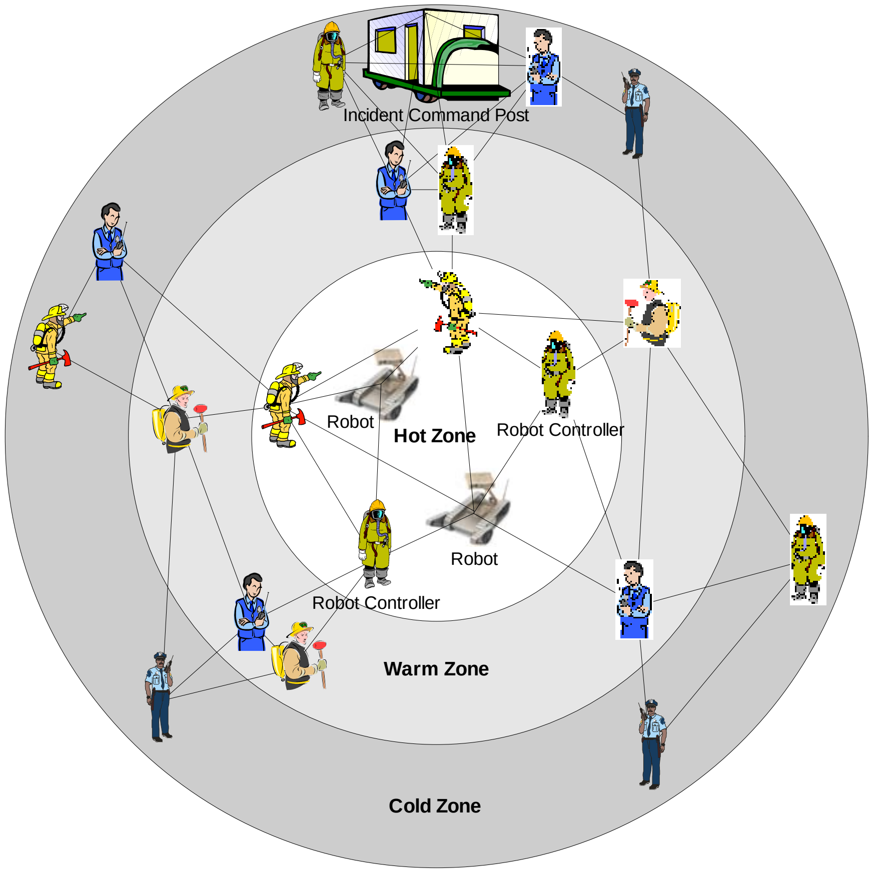

Figure **1**. A wireless mesh network is formed at a disaster site when first responders are deployed with ad hoc multi-hop wireless nodes. Connections are made to destinations normally out of range or not within line of site by hopping packets from one node to another node until it reaches the destination.

A typical wireless ad hoc disaster site network is shown in Figure 1. First responders, a multidisciplinary group of individuals dedicated to the task of search and rescue for survivors at a disaster site, are the front line crisis response team. Communication among team members is of paramount importance for the dissemination of tasking instructions and collection of site-specific data. Technology designed for mobility, such as laptop computers and personal digital assistants, is now being used by first responders. These devices are connected together through wireless local area networks (WLAN).

One of the newest and most promising technological advances to assist search personnel is rescue robotics. Robots are used for entering areas where humans and canines cannot, due to either safety or space confinement reasons. The robot controller will send control data to the robot and the robot will send sensor and video data back to the controller. The next evolutionary step will be to integrate the robot control and data collection into the WLAN at the site.

Deploying a WLAN at a disaster site can be difficult and time-consuming. The IEEE 802.11 standard is the most popular wireless network implementation, but its strict infrastructure requirements pose significant problems with respect to communication reliability and, thereby, degrade the effectiveness of using tools such as rescue robots. Wireless communication tends to fail due to interferers, unidirectional links, line-of-site loss, shadowing, and multi-path fading.

Current 802.11 implementations are not ad hoc — they are not able to dynamically re-route traffic to accommodate physical layer link disruptions. They rely on access points connected to wired network nodes. If a node moves out of range of an access point, connectivity to the WLAN is lost, even if the node is close to another node that has connectivity to the network, as shown in Figure 2. The inability of an 802.11 WLAN to relay, or hop, IP packets across multiple nodes causes bottlenecks that decrease the reliability and reception quality of streaming data, such as video from robots. Visual images from the robot are distorted and difficult for the controller to interpret. An ad hoc mesh network architecture for wireless communication solves most of these problems.

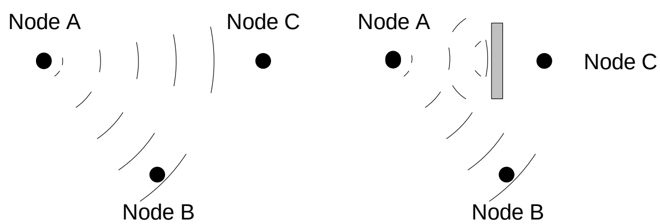

Figure 2. Current IEEE 802.11 WLAN implementations are not ad hoc and packets cannot be delivered to nodes that are not neighbors of the source node. In these network layouts node C cannot communicate with node A due to either being out of range or having the signal obstructed. Therefore, node C cannot receive packets destined for it even though node B is a neighbor of both nodes A and C.

An ad hoc mesh network does not rely on access points for communication. Instead, it dynamically routes data through one or more nodes in the network to get to its destination. This type of network adapts to the ever-changing topology of a truly mobile network. Nodes circumvent interferers and multi-path fading by automatically detecting and using better paths through the network's changing infrastructure, as shown in Figure 3. Ad hoc networks can be deployed almost instantly since nodes dynamically maintain infrastructure. First responders will focus on the disaster site and not on setting up communications system hardware.

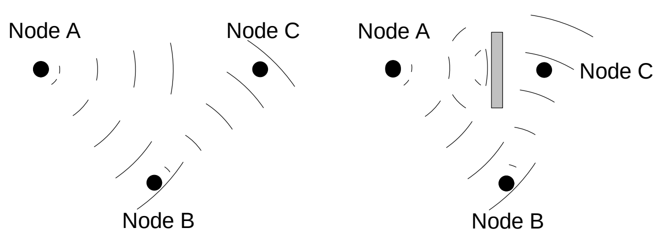

Figure 3. Ad hoc wireless networks can deliver packets to nodes that are not neighbors of the source node by hopping the packet through an intermediary node. In these network layouts node C can receive packets from node A even though it is not a neighbor of node A. This is accomplished by hopping the packet through node B.

Wireless networking is notorious for poor video performance as a result of interferers, shadowing, multi-path fading, and loss of line-of-site. To provide increased streaming multimedia quality over wireless networks, Nova Engineering is developing the Adaptive Link-layer Intelligence for Enhanced ad hoc Networking (ALIEN) technology, adding intelligence to the layer two link level to improve the performance and reliability of ad hoc routing algorithms. Methods employed to identify and predict time-varying channel perturbations result in route changes through nodes with better connectivity. This reduces packet loss that typically occurs by using common shortest path nodes, and provides reliable network performance.

The technology illustrated in this paper is not limited to the first responder market. Other markets that benefit through the implementation of this research effort include:

- Remotely controlled robotic surveillance by law enforcement and military personnel. Local law enforcement could send robots into dangerous situations to gather information. The military could use robots for searching caves or abandoned buildings without putting personnel in harm's way.
- Local news-casting markets can deploy a wireless mesh network around the local area and transmit audio and video streams back to the station without having to transport larger microwave equipment.
- Local law enforcement agencies could transmit live video streams from their vehicles to central dispatch, greatly increasing situational awareness in real-time. This enables additional assistance to be rendered to fellow officers, as needed, without the officer calling in for assistance.

1.2. NovaRoam

To solve many of the traditional 802.11 type of wireless networking issues, Nova Engineering introduced the first commercial mobile ad hoc wireless router product line, called NovaRoam.

The redundant communication paths provided by ad hoc mesh networks drastically improve fault tolerance for the network. Additionally, the ability for data packets to "hop" from one user to another effectively extends the network coverage area and provides a solution to overcome non-line of sight (LOS) issues.

Mobile applications present additional challenges for mesh networks as changes to the network topology are swift and widespread. Such scenarios require the use of MANET technology to ensure communication routes are updated quickly and accurately. MANETs are self-forming, self-maintained, and self-healing, allowing for extreme network flexibility. While MANETs can be completely self contained, they can also be tied to an IP-based global or local network (e.g. Internet or private networks). These are referred to as Hybrid MANETs.

There are numerous MANET protocols currently in existence, including AODV (Ad hoc On-demand Distance Vector), TORA, DSR, and OLSR. Each protocol has evolved over time to better suit the dynamic nature of mobile ad hoc networks.

1.3. MANET Protocols

Numerous MANET protocols exist; yet very few have been implemented outside of the research community. Each protocol has evolved over time to better suit the particular requirements of various types of mobile ad hoc networks. MANET protocols are typically categorized as either proactive or on-demand (reactive). Proactive MANET protocols update routing information in a proactive manner by exchanging route information at periodic intervals. The exchange of table-based route information is evenly distributed across the wireless network. As a result, routes are established prior to being needed, providing a wireless network that is low in latency, at the expense of increased overhead.

Rather than distribute all route information across the entire network, On-demand MANET protocols perform route maintenance only when required. On-demand protocols create less network overhead since the exchange of routing information is localized rather than evenly distributed. The result is a network with less overhead, at the expense of increased latency due to the route discovery process.

1.4. AODV

The NovaRoam Mobile Router is unique as it uses an embedded MANET protocol called AODV that works dynamically to establish and maintain routes, adapting quickly to changing link conditions. As its name implies, AODV is an on-demand routing protocol. Routes between nodes are built only as requested by source nodes. These routes are maintained locally until they are no longer needed by the source nodes or a link breakage occurs. As powerful as the AODV algorithm is, there are some inherent issues that occur when deploying it in a real-world environment.

Nova Engineering has already overcome some of the issues inherent with the current AODV algorithm. AODV sends small packets (all less than 100 bytes) for both route discovery and route maintenance. A phenomena in wireless transmission, coined the Grey Zone, can occur in which packets of small sizes have a higher probability of proper transmission than that of packets of larger size (Figure 4). When a neighbor falls into the Grey Zone it will allow the

AODV algorithm to establish a route through it, not taking into account the high packet loss associated with large packets.

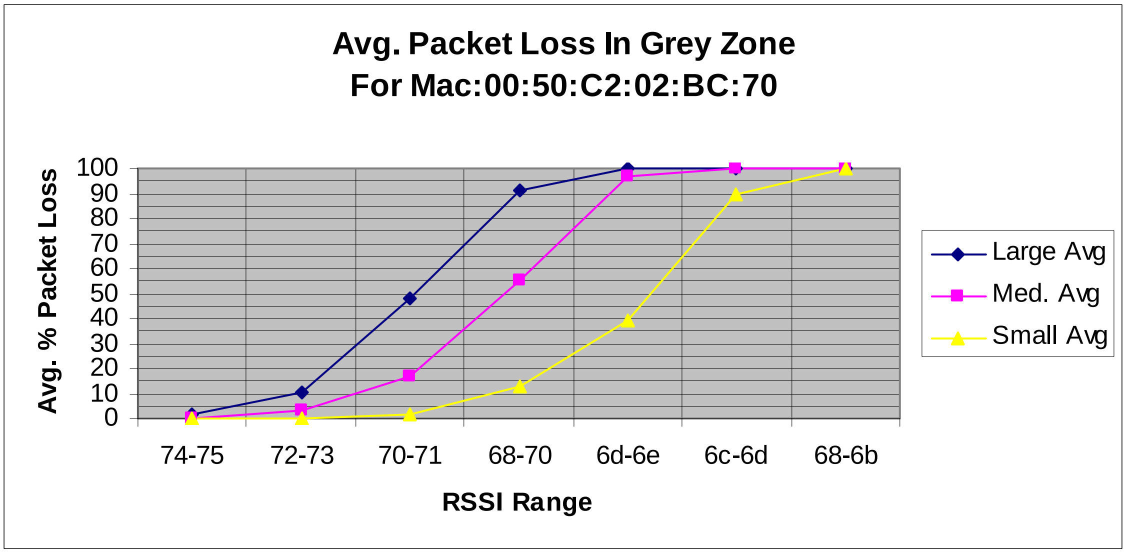

Figure 4. An example of Grey Zone for different packet sizes in different RSSI ranges.

The NovaRoam platform circumvents the Grey Zone problem by calculating the receive signal strength indicator (RSSI) ranges or thresholds that fall into the Grey Zone. These thresholds are then used to filter out packets that do not register appropriate RSSI levels. The filtered packets prevent AODV from establishing routes through neighbors that will have poor performance for larger packets.

2. ADAPTIVE LINK-LAYER INTELLIGENCE FOR ENHANCED AD HOC NETWORKING

The objective of the ALIEN technologyis to improve link reliability and throughput in ad hoc networks. This research effort is based on the key idea that adding link level intelligence to mobile ad hoc networks improves the performance and reliability of ad hoc routing algorithms. Many desirable multimedia services such as Voice over IP, streaming audio, and video streaming require guarantees on throughput, delay, and probability of data loss. The unreliable nature of wireless channels, due to time-varying interference, fading, shadowing, channel collisions, unidirectional links, and other channel effects, makes such guarantees very difficult to provide. Adding intelligence to the link level that both identifies and predicts such channel effects is critical in supporting multi-path routing over a wireless network.

This technology adds link level intelligence to wireless networks through improvements in link level protocols, such as the neighbor discovery module of the Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) ad hoc routing algorithm, and using Hidden Markov Models (HMMs) to recognize sources of interferers and predict changes in link quality. The ALIEN technology is designed around this link level intelligence and is independent of any specific ad hoc routing algorithm. The following sub-section describes the link level protocol and HMM portion of the proposed architecture.

2.1. Improved Neighbor Discovery

As the first step in realizing a more intelligent link level, a neighbor discovery algorithm needs to be incorporated into the link level protocol. The NovaRoam platform’s current ad hoc routing algorithm, AODV, constructs the neighbor list at the network layer. This method detects bi-directional links between the neighboring nodes, however, does not provide any detail on the quality of the link. The lack of a link quality threshold in neighbor discovery can mislead most MANET algorithms, such as AODV, to include neighbors that have relatively poor link margins only good enough to sustain the neighbor discovery protocol. This results in unnecessarily poor network performance which might have been avoided by routing through another neighboring node. By integrating the neighbor discovery algorithm into the link layer and developing link quality thresholds to evaluate neighbor node reliability, the neighbor list assists an ad hoc routing algorithm in choosing the correct neighbor to route through.

2.1.1. Neighbor Discovery at the Link Layer

The neighbor discovery algorithm of the NovaRoam platform is based off of the neighbor discovery module of the TBTPF protocol. TBTPF is a proactive, link-state routing protocol designed for mobile ad-hoc networks. It provides hop-by-hop routing along shortest paths to each destination node. Each node running TBTPF provides a "source tree" that describes the shortest paths, using a modified Dikstra shortest path algorithm [1], to all reachable nodes in the network topology. TBTPF nodes provide their neighbors with partial lists of their source tree to keep them informed of the best possible paths and topology changes. Within TBTPF's architecture is a neighbor discovery (TND) module that enables rapid detection of bi-directional links between local and neighbor interfaces. The TND module provides a neighbor table to support routing decisions by an ad hoc algorithm.

To develop link quality threshold metric monitoring at the link layer, the TND protocol must incorporate enhancements to the neighbor table structure. Preliminary evaluation of the protocol demonstrates a competent neighbor discovery algorithm that can be modified for this research. The current neighbor table provides information for each node such as router ID, current link status (lost, unidirectional, or bi-directional link), status lifetime, hello sequence number, hellos lost, and sequence number history. This research effort expands neighbor node knowledge so that signal strength and bit error rate (BER) information will also be maintained.

The TND neighbor list link quality status, or state information, is expanded to include more link states, next state predictions, and state transition probability information. Providing such information in the neighbor list enables ad hoc routing algorithms to make preemptive route switching decisions based on link quality and stability.

2.1.2. Link Layer Metrics

In order to incorporate link quality into the neighbor list, all observable link level metrics provided by the existing NovaRoam product platform and any possible supplementary metrics that can be incorporated into the architecture must be identified. Currently, the NovaRoam architecture provides a variety of observable packet level, Reed-Solomon (RS) error correction and Signal-to-Noise Ratio (SNR) metrics that are used to describe the link channel.

The NovaRoam ad hoc router provides packet level metrics such as Good Positive and Good Negative (when forward error correction (FEC) is enabled) Correlation Hit metrics. These statistics provide insight into channel contention and interference issues for a link. A running count of both Good and Bad CRCs is provided as a useful packet level metric. Automatic Repeat Request (ARQ) and Multiple Access with Collision Avoidance (MACA) level statistics are also useful to detect link contention.

Reed-Solomon codes, used to detect and correct errors by recovering information symbols, provide observable metrics such as the number of correct symbols in a transmission. Additional metrics such as locations and distribution of symbols can be incorporated into the current NovaRoam product architecture with minimal effort, thus providing valuable data for this evaluation with little investment.

Matched filter detection, which correlates the received signal with the desired user's time reversed spreading waveform in the target ad hoc router, provides a variety of link level metrics such as a received signal strength indicator (RSSI) and noise level. An SNR metric is beneficial in describing the relationship between RSSI and interference.

2.2. Link-Layer Prediction Through Intelligence Subsystems

Adding intelligence to the link level that both identifies and predicts channel phenomena such as time-varying interference, fading, shadowing, channel collisions, unidirectional links, and other channel effects is critical in supporting multi-path routing over a wireless network (Figure 5). The proposed architecture consists of two link level intelligence subsystems: an Interferer Source Recognition Engine (ISRE) and an Interferer Source Prediction Engine (ISPE). The first subsystem monitors link level metrics and recognizes possible sources of signal distortion in the current link channel. The second subsystem implements a user configurable constraint model that predicts if the next set of observations from the link level is acceptable for the channel. Such intelligence allows for the optimization of multipath routing, providing the ability to preempt route loss in ad hoc networks, and enable other corrective measures to the radio such as real-time power level modification to avoid path signal fading.

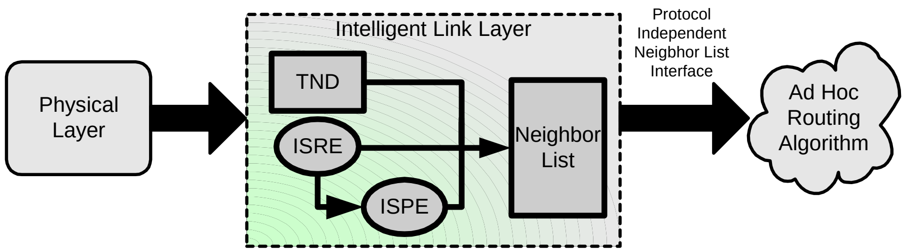

Figure 5. The Intelligent Link Layer provides a protocol independent neighbor list that any ad hoc routing algorithm can utilize by first identifying neighbors and then monitoring and predicting the quality of the links to those neighbors.

2.3. Link-Layer Quality Prediction Through the ISRE Subsystem

The ISRE subsystem provides the link level with the ability to recognize different interferer sources, causing signal distortion over the communication channel, by observing variations in the metrics used to characterize the signal. Based on prior experience with speech recognition, and understanding that the link level can be described by a unique set of observable metrics, the Hidden Markov Model is a good candidate for link channel quality recognition. HMMs are a class of probabilistic models that are generally applicable to time series or linear sequences. A HMM describes a probabilistic process over a finite state machine having a set of: states (Q), Output alphabet (O), Transition probabilities matrix (A), Output probabilities matrix (B), and an initial state probabilities vector (Π). The output probabilities matrix B is termed the confusion matrix, containing the observable states given a particular hidden state. In other words, each state produces an output with a certain probability B. Usually the states, Q, and outputs, O, are understood, so an HMM is said to be a triple, (Π, A, B).

$\Pi = \{\pi_i = Pr(q_i \text{ at } t=1)\}$ the vector of the initial state probabilities
$A = \{a_{ij} = Pr(x_j \text{ at } t \mid x_i \text{ at } t\text{-}1)\}$ the state transition matrix
$B = \{b_{ij} = Pr(y_i \mid x_i)\}$ the confusion matrix

Each probability in the state transition matrix and in the confusion matrix is time independent — that is, the matrices do not change in time as the system evolves.

A set of HMMs, each representing a possible source of signal distortion over the wireless channel, defines the framework of the ISRE. The main function of the ISRE is to provide the capability to evaluate a sequence of observations and match it to the HMM with the greatest probability of producing that sequence. The ISRE provides up-to-date interferer source information to other link level subsystems, such as the neighbor list associated with the TND module. A basic left-right HMM and corresponding Baum-Welch training algorithm[2,3] is used to implement the ISRE. A left-right HMM stipulates that the model always starts in a particular case.

The Baum-Welch training algorithm is used to find the model that provides the maximum likelihood (ML) estimation of the training data. The algorithm begins with an initial model and runs each training data sequence through it. At each iteration the algorithm modifies the model to describe the maximum likelihood path used to generate the sequence.

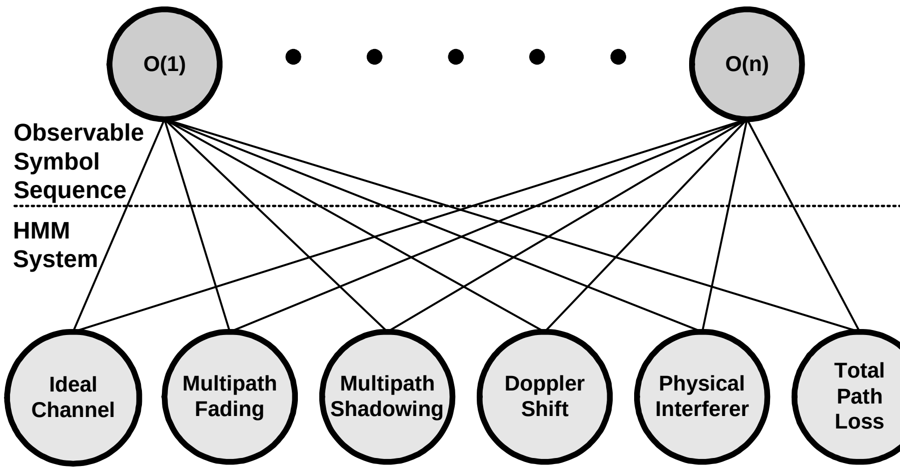

Figure 6. The probability of each HMM system in the ISRE is calculated for each input symbol sequence. The ISRE then ranks each system and determines the most likely current state of the link channel.

The ISRE receives a multi-dimensional feature vector from the link level and produces a sequence of symbols using vector quantization (VQ). The generated symbol sequence is then evaluated and matched to the sequence in the HMM with the greatest probability of producing that sequence (Figure 6). The ISRE also keeps a history of each recognition output probability set in a history matrix, which provides input to the secondary intelligence subsystem. The HMM model set needed for the ISRE identifies various causes of signal distortion at the link level such as multipath reception (multipath fading, shadowing, and Doppler shifts), fading, and physical interferers.

Data collection is the primary obstacle to overcome during the development of the HMM system in the ISRE. A large amount of data is needed to both train and test the HMMs. Data collection consists of setting up link level models to demonstrate the particular phenomena. A series of trial simulations is completed and the observable metrics, defined in Section 2.1.2, are recorded as sequences of multi-dimensional feature vectors. It is important to provide a good variation of feature vectors for each HMM by changing parameters in the simulation, such as received signal strength, number of co-located nodes, and amount of network traffic. It is important to provide the correct amount of training data variation to produce accurate HMMs.

The data is used to train each model, which involves the quantization of the feature vectors into sequences of symbols using VQ, and using the Baum-Welch training algorithm to train the HMM. Experimentation with different codeword sizes associated with the VQ and the number of states describing the HMM should be performed. Analyzing the effects these configurable parameters have on the recognition rates of the HMM provides useful knowledge and insight to aid in optimizing the system.

Each trained model is tested against the collated test data set. The recognition rate of each model is evaluated and compared to previous models. The goal of this research is to have a 90% Interferer Source recognition rate. Part of this research process involves redefining what physical link channel phenomena the HMMs describe.

Open source implementations of HMM, Baum-Welch training algorithm, and VQ have been evaluated and used to develop the initial ISRE system.

2.4. Ad Hoc Routing Optimization through the ISPE Subsystem

The second intelligence subsystem is the Interferer Source Prediction Engine (ISPE) and is shown in Figure 7. The ISPE is a constraint model that can determine when the probability of generating the final state – the total path loss state given current model approximations – of the model,is imminent. The history matrix, which provides the probabilities of each ISRE model reoccurring, can be used by the ISPE to evaluate its next state prediction. The ISPE provides a preemptive route status mechanism to the link level subsystems by incorporating valuable prediction information into the neighbor list of the TND model.

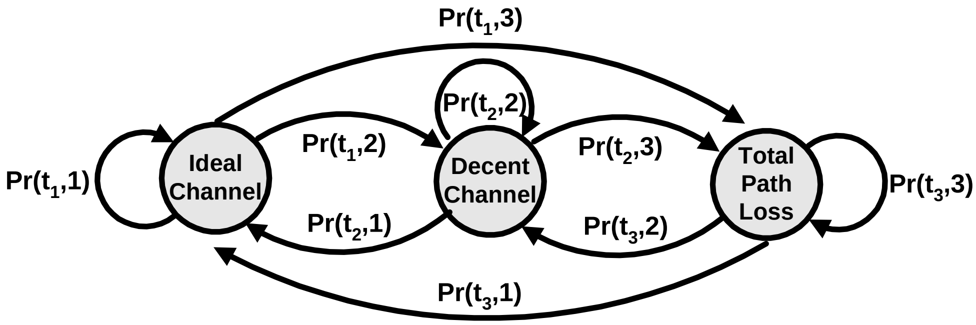

Figure 7. The ISPE subsystem determines when the probability of generating the final state of the model is imminent.

The ISPE allows the intelligent link level architecture to expand beyond simply improving ad hoc routing decisions. The ability to predict next link channel states enhances power saving techniques by predicting when to adjust power output levels. The ISPE contains multiple "link quality" constraint models that provide usefulness for different applications ranging from providing maximum data reliability to trying to allow maximum throughput.

The performance of this algorithm during various state transitions can be characterized, and a plan cam be formulated to make use of the intelligent link level and its predictive state transition properties to improve its performance.

The AODV routing algorithm can be enhanced by using this new link level intelligence The enhancement improves route stability and handoff time by predicting when path loss is about to occur. The constraint model can be set up to simply use current link quality thresholds that will inform the routing algorithm when a neighbor link is too poor to use reliably. This enhancement eliminates a link reliability issue discovered in AODV. Currently the AODV algorithm will continue to use a neighbor node whose link quality is good enough to sustain the underlying AODV routing traffic. The algorithm has no way of identifying that the traffic being routed through this neighbor is not being routed reliably. This is a major cause for poor performance with video and voice traffic through wireless networks.

3. CONCLUSIONS

Use of adaptive link-layer intelligence enhances the quality of service in mobile ad hoc networks. Predicting link-layer quality is accomplished through the use of an Interferer Source Recognition Engine. Routing is then optimized using an Interferer Source Prediction Engine. Both of these subsystems take advantage of Hidden Markov Models to predict link conditions. Incorporation of link-layer intelligence enhances the effectiveness of the AODV routing algorithm and improves communication of data over wireless networks.

REFERENCES

1. R. Ogier, F. Templin, M. Lewis, "Topology Dissemination Based on Reverse-Path Forwarding (TBRPF)", RFC 3684, Feb. 2004.
2. L. R. Rabiner, B.H. Juang, "An Introduction to Hidden Markov Models", IEEE ASSP Magazine, Jan. 1986.
3. V. Paxson,, G. Almes, J. Mahdavi, M. Mathis, "Framework for IP Performance Metrics", RFC 2330, May 1998.
4. S. Mao, D. Bushmitch, S. Narayanan, and S. S. Panwar, "MRTP: A Multi-Flow Real-Time Transport Protocol for Ad Hoc Networks", IEEE Fall VTC, Oct. 2003.
5. L. R. Rabiner, "A Tutorial on Hidden Markov Models and Selected Applications in Speech Recognition", in *Proceedings of the IEEE*, Vol. 77, pp.257-286, February 1989.