PROGNOSTICS AND HEALTH MANAGEMENT FOR WIRELESS TELEMEDICINE NETWORKS

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ABSTRACT

Prognostics and health management has been widely used in predicting the time at which a system will no longer perform its intended function. This article aims at providing a detailed discussion of reliability optimization for wireless telemedicine network by using a prognostics approach. The science of prognostics, which is based on the analysis of failure modes, detection of early signs of wear and aging, and fault conditions, has been applied to electronic components and systems as well as structural monitoring. Using data-driven prognostics techniques, the condition of a network can also be monitored using operational data related to data packets as they are delivered across the network. Prognostics are particularly important for wireless telemedicine networks since these networks must operate reliably irrespective of abruptly changing operating conditions in order to support life-saving missions.

INTRODUCTION

Technical advances in multimedia and telecommunications have enabled healthcare services to reach more people. Telemedicine network infrastructure provides a crucial communication link between medical service providers and patients in a way not limited to geographical locations [1]. Wireless networks of different types serve target customers with different requirements, from general-purpose consumer electronics to telemedicine supporting a diverse range of healthcare applications, including critical lifesaving missions with far more stringent requirements. Correspondingly, there are different performance and reliability requirements for different situations. Any disruption to the telemedicine network can lead to link outage, potentially leading to severe consequences. For example, a tele-robotic surgery that is suddenly interrupted can cause a fatality. Applications such as remote patient monitoring, medical record retrieval, medical consultation for rural areas, and real-time on scene paramedic support and tele-diagnosis, all have different levels of tolerance to delay and service quality. To address the importance of network reliability in telemedicine, quality of resilience has been adopted [2]. By understanding various common factors that cause network disruption, the extent of network performance degradation can be predicted and preemptive actions can be taken to mitigate the risk of a link outage.

The network backbone forms a core component of any wireless telemedicine system and is often the bridge between the healthcare service provider and end user. Failure of the radio link can lead to service interruption that may result in loss of critical time for emergency treatment, particularly in systems incorporated with accident recovery. Network failure has a number of implications, ranging from intermittent outage to loss of captured data. Outdoor wireless networks operate under harsh environments, often under the influence of a combination of uncontrollable and unpredictable factors. Failure is often caused by fading, rain attenuation, and depolarization [3]. Understanding the impacts of these failure modes would allow necessary corrective actions (such as allocation of adequate system margins) to be taken prior to an actual failure. A number of system parameters can be adaptively adjusted to ensure maximum network availability and reliability through prognostics and health management.

The word “prognostics” usually refers to the forecast of what might happen based on signs or symptoms in making a prognosis, meaning that prognostics can predict what will likely happen to a system under certain operating environments so that reliability can be optimized. Relevant data can be collected during normal operation of the telemedicine system.

PROGNOSTICS AND NETWORK HEALTH MANAGEMENT

CONDITION-BASED MONITORING

Generally, prognostics involve predicting the future health of a system based on various signs or symptoms. Prognostics and health manage-

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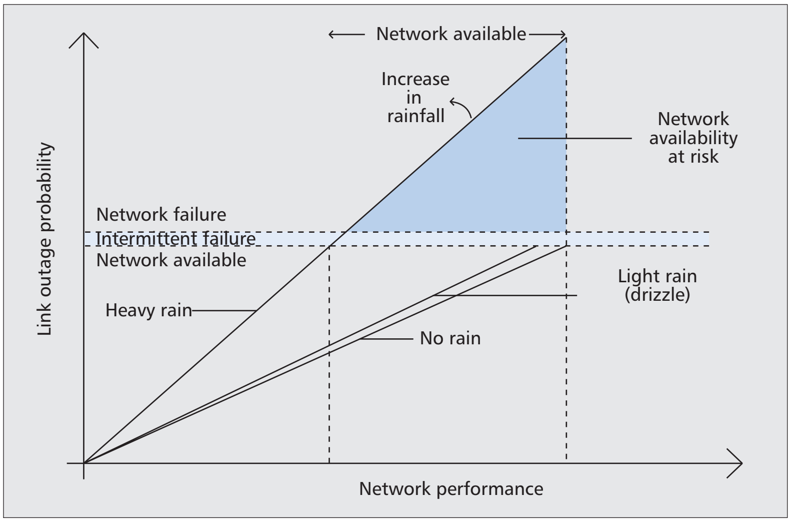

Figure 1. *Prognostic network monitoring for link availability.*

ment (PHM) is a method that permits the assessment of reliability in electronics components and systems [4]. PHM has been used in condition-based maintenance (CBM) in industries ranging from consumer electronics to aerospace as a technique implemented to estimate the remaining useful life of a given system. PHM methodologies have long been used in various sectors of the consumer electronics industry to provide advanced warnings of failure or performance degradation, reduction in life-cycle cost, and unscheduled maintenance. For example, PHM used in consumer electronic products monitors life-cycle loads where modeling of stress and damage provides information about anticipated performance or physical degradation of the product under different operating conditions. Various parameters of a wireless network can also be used to assess performance degradation and failure due to variable operating conditions in much the same way.

One of the major objectives of PHM is condition-based fault management. Detection of a fault is usually accomplished when a certain network performance metric falls below its predetermined threshold that affects the Quality of Service (QoS). Fault management entails symptom detection followed by problem isolation. Diagnostics can attempt to fix a problem depending on the nature of the problem. For example, the transmission power can be dynamically elevated on a temporary basis when heavy rain disrupts a wireless link. A log keeping track of each failure event can be used for building a prognostics model for future failure prediction. When burst errors are detected in successions, cumulative network damage modeling can be built to estimate the extent of network degradation.

PHM implementation requires information about network data traffic to be collected and analyzed. It uses data transmission performance of the wireless network to detect abnormalities that may subsequently cause network degradation and failures. Based on network performance, it is possible to build a statistical model that describes the behavior of the radio link under different operating environments. This allows prediction of what the data packets in transit are expected to experience based on previous packets. Past network performance provides an insight into parameters such as:

- Latency: the time delay expected for a data packet.
- Bit error rate (BER): the number of corrupted bits found in a string of data.
- Interference: the source and severity of interfering signals.
- Hardware failure: where and which piece of hardware will fail and the mean time to repair.

By understanding various major factors that affect the operating reliability of a wireless network, it is possible to apply PHM techniques to improve network reliability in different situations. With CBM, the network health can be maintained by adjusting a number of parameters in response to any performance degradation. For example, adaptive coding, modulation and power control, and data throughput, can be dynamically adjusted as network conditions vary.

IMPLEMENTATION

Technical approaches to prognostics are broadly classified as data-driven approaches, model-based approaches, and hybrid approaches that blend the implementation of both data-driven and model-based approaches. In the case of data-driven prognostics, network traffic data is used where the communication system operation is not comprehensive and development of an accurate model is not feasible due to system complexity. The main advantages of using data-driven prognostics are fast deployment and the ability to provide system-wide coverage including network hardware. Also, data analysis is possible with software. However, the main drawback is that potentially vast amounts of data as well as domain knowledge are required for training [5]. The effectiveness of data-driven prognostics depends on both quality and quantity of network traffic data. Feature extraction may involve processing of data with excessive error and packet loss.

Model-based prognostics require understanding of the system operating environment such that a physical model can be built for prediction of a network failure due to changes in operating conditions. For example, factors that cause temporary link outage, fading, and excessive loss may be modeled. Modeling of terrain elevation would also help with predicting link degradation; the effects of buildings and trees can also be modeled.

Network failure is prevalently stochastic in nature [6] such that failure occurrence can be mathematically described by statistical modeling of network parameters. For example, temporary link outage due to heavy rainfall can be modeled by information about rain-induced attenuation and depolarization [7]. A scenario where a link outage can be forecasted when rainfall reaches a certain rate is shown in Fig. 1. Network performance degrades as the rain becomes heavy until it reaches a point when the signal is too weak to be received. The shaded area in Fig. 1 shows where network availability is affected by the rate of rainfall. Optimizing network reliability in this area warrants the use of health monitoring.

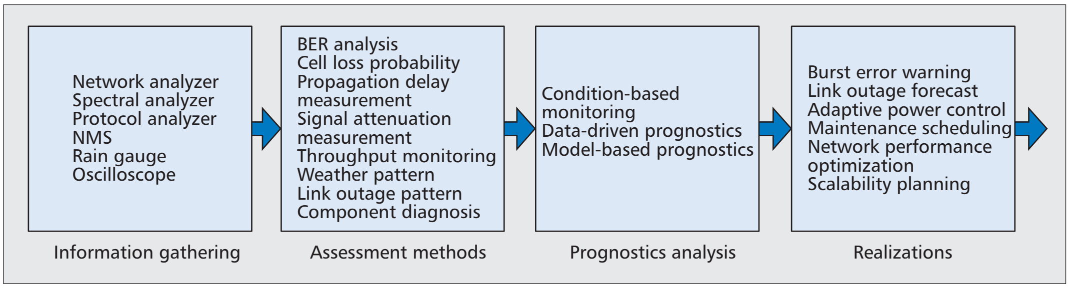

Figure 2. *Prognostics and network health management framework.*

The extent and rate of network degradation is determined by the cause and duration of outage. The network outage profile can be applied in conjunction with network models to assess and predict network degradation due to different environmental conditions.

Prognostics supports link prediction through statistical modeling so that reliability and performance can be balanced. In response to the network performance degradation due to attenuation, parameters such as transmission power and data rate can be adaptively regulated to ensure reliability under varying operating conditions.

The hybrid approach makes use of both data-driven and model-based approaches by gathering network traffic information to build a statistical model. For example, a model to minimize the effects of rain attenuation and depolarization on network availability for a given site can be developed by collecting long term statistical information about rainfall of the site. A "post-estimate" fusion for uncertainty management is most appropriate by using a hybrid approach since rainfall inherently links to uncertainties. This narrows the uncertainty intervals of data-driven or model-based approaches, thereby improving performance of an estimator with different sets of data, namely, rain statistics, rainfall attenuation, and depolarization. Fusion is achieved by making use of quality assessments that are allocated to the individual estimators based on different parameters, for example, known extent of attenuation due to specific rainfall rate for a given polarization.

REAL-TIME NETWORK ASSESSMENT

From the collected network and environmental data, the network status can be assessed by data-driven prognostics through one of the following methodologies [4]:

- Canaries: The term Canary originates from the deployment of canary birds historically used in coal mines to detect the presence of gob gas. Data packets can act in much the same way as canary birds flying in a mine shaft as they propagate through the network, and the mechanism is very similar to path discovery through maximum transmission units (MTU). Network diagnosis is carried out based on utilization of canaries and link degradation models, autonomous risk mitigation by self-reconfiguration, and self-repair through implementation of various network parameters with self-cognizant prognostics.
- Failure precursors monitoring: A failure precursor is a data event that indicates an imminent failure. It usually entails a gradual change in some kind of measurable variable that will lead to a failure as a consequence of such change. For example, an abrupt drop in the received signal power may indicate network degradation due to a change in the surrounding environment. Various parameters such as cell delay/loss, BER, and utilization of the network, can be monitored for any signs of performance degradation.
- Environmental based modeling: Statistical models can be constructed from previous data packets as well as any change in operating environments. The extent and rate of network degradation is determined by the cause and duration of outage. The network outage profile can be applied in conjunction with network models to assess and predict network degradation due to different environmental conditions.

Prognostics and network health management can achieve a number of objectives, such as those featured in Fig. 2.

Data collection is a vital part of PHM and requires the use of network management systems (NMS) to obtain network parameters. Several methods for PHM implementation have been proposed, including monitoring and analysis of parameters that are precursors to an impending failure. The monitoring of the operating environment and network parameters is a fundamental step in the PHM implementation. In order to accurately assess the network health and predict a link outage, a variety of monitoring features may be required in order to obtain characteristics of these parameters, such as magnitude, variation, duration, rate of change, and statistical behavior.

Selection of parameters to be monitored for the PHM implementation is based on their relationship to network degradation and possible causes of failure. These are usually selected from knowledge obtained from past experience; systematic methods such as the Failure Modes, Mechanisms, and Effects Analysis (FMMEA) method to determine what parameters to monitor [8]. This would involve data analysis of each node within the system to assess the nature of error. Sometimes an error can remain undetected as encoders cannot provide a 100 percent successful error detection rate. Codewords that contain errors can therefore get through from time to time. This usually occurs when the error pattern happens to be the same as that of the designed codeword for transmission. What is received with error is converted into another codeword that may be misinterpreted by the decoder as something else but not the same as what was originally sent. In such situations, the decoder does not have the necessary information to distinguish between a legitimate codeword (of different information content) and a corrupted codeword exhibiting the same bit pattern.

Network Component	Failure Precursor
Demodulator	• Phase shift • High frequency noise • Demodulator hardware degradation • Synchronization problem • Clock drift • Received signal strength
Antenna	• Wind loading • Physical damage • Wet surface • Connector oxidation • Misalignment
Channel (air interface and feed lines)	• Burst error • Packet loss • Latency (time delay) • Interference and noise • Intermittent outage
Network Management System (NMS)	• Lengthy response time • Excessive CPU utilization • Efficiency decrease • Data congestion • Power failure
Routing Control	• Re-transmission rate • Packet loss • Buffer overflow

Table 1. *Common failure precursors.*

Other errors include random and burst errors. Random errors are statistically independent events that occur on channels due to additive noise, for example, Gaussian noise. Such channels of independent-error are said to be memoryless since knowledge of previous channel conditions would not provide any information on current or future error behavior. In contrast, burst errors are not independent; these errors occur such that consecutive bits suffer from a higher probability of errors, usually dependent on previous channel conditions. This condition is referred to as channels with 'memory' although the channel itself does not really have any information storage capabilities. Condition based channel maintenance can be easily accomplished with such knowledge.

SELF-COGNIZANT PROGNOSTICS

Prognostics and health management for wireless networks that continuously monitors the network performance using network management algorithms that controls BER, latency and packet loss rate on throughput performance enables prior prediction and avoidance of network failures. Prognostics in a self-cognizant network allows information gathered from uncertainty analysis to be used in anticipation of an event. In situations where more users are competing for channel bandwidth, dynamic bandwidth allocation for several paramedics operating in a close proximity so that parameters such as adaptive power control and adaptive modulation can be adjusted to combat the effects of link degradation. These network parameters can be regulated both throughout the entire telemedicine network [9] and within the local area network (LAN) that serves a group of paramedics.

In some networks, such as telemedicine networks that facilitate paramedics carrying out their duties on-scene, data communication with the hospital may involve multi-hop wireless networks. Some paths along the network may be temporarily disrupted. Self-cognizant capabilities can be incorporated in a fault localization system such that the performance of any part of the network can be monitored [10]. Data packets that go through certain hops with extensive delay or have been lost can serve as an indication that the relevant hops should be isolated and diagnosed. It may also be necessary to automatically initiate a re-transmission of the lost packets.

Fault isolation and diagnostics can be signified by a precursor [11]. Some common failure precursors for a wireless network are listed in Table 1. In addition to precursor monitoring, another method is to use redundancies. For example, by using two signal paths of alternate polarization [12], a separate link can be deployed as a backup in the event of link failure or congestion. This can be accomplished by mounting antennas of vertical and horizontal polarizations perpendicular to each other. Such backup is extremely important in life-saving telemedicine applications since any temporary network interruption can lead to fatal consequences.

The PHM methodology can be generalized as shown in Fig. 3. The first step entails a virtual life assessment, where data traffic, network architecture, failure modes, and physics-of-failure (PoF) models are the inputs to obtain a reliability (virtual life) assessment [13]. From the virtual life assessment, critical failure modes and failure mechanisms such as link outage and hardware failure can be prioritized. Existing network conditions from NMS, protocol analyzers, and maintenance and inspection records can also be used to identify any irregular network conditions and parameters. Typically, an NMS or protocol analyzer will generate a list of information related to packets that traverse the network. The monitoring parameters and any network nodes for PHM can be determined based on this information.

Statistics about network health can be used for the prediction of network outage. A link failure can be expected when the rate of rainfall reaches a certain level thereby reducing the percentage of link availability. Network health information can be used to assess the link condition so that certain network parameters can be adjusted in order to combat performance degradation. Some networks do not have direct link between the transmitter and receiver so that data transmission must go through some nodes or repeaters. When the network degrades, certain paths along the network may be temporarily disconnected from the overall network to avoid network disruption.

Canaries can be used to track the condition and link degradation of any part of the network. They will mitigate failure risks by early warning of impending failures. The use of data packets as canaries for early warning of network degradation and impending failures allows risk mitigation

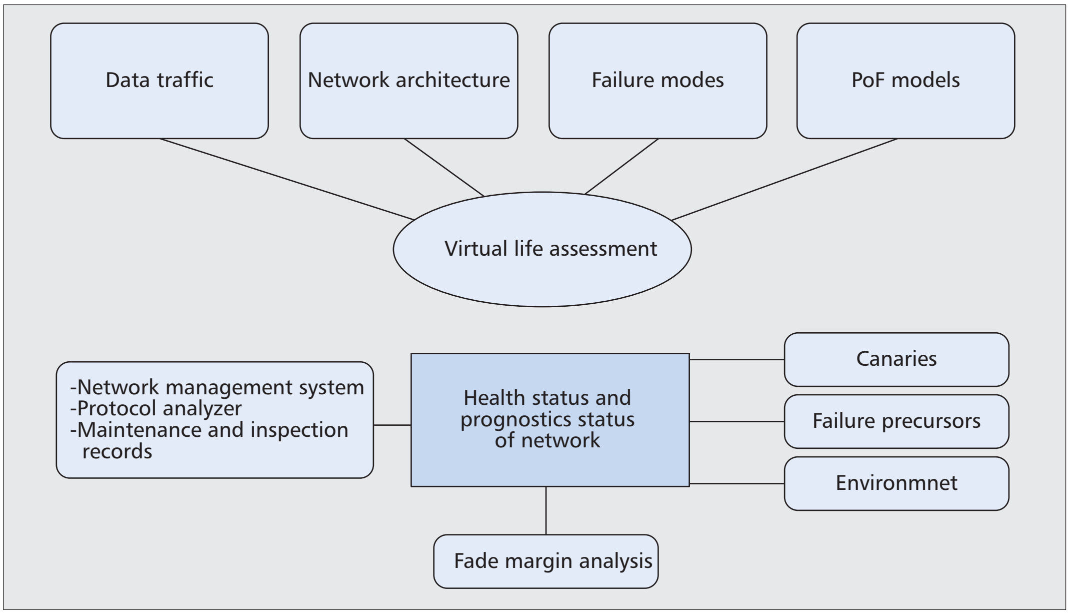

Figure 3. *General PHM methodology.*

Canaries can significantly reduce the uncertainties in the estimation of link conditions since each canary is tailored to a known failure mechanism to match the behavior of the functional elements such as link attenuation, depolarization, and interference that are being monitored.

options to be automatically implemented, such as re-routing or adjustment of transmission power in response to different uncontrollable degradation sources in situations like rain-induced attenuation and moving physical obstacles.

Analysis of the canaries can be used to construct a statistical model that provides certain information of the network status. Any abnormally long packet delay or excessive data packet loss may indicate network congestion or a node failure. Analysis of what these packets experience can be done through NMS for fault identification and isolation that incorporate error detection and correction circuits, self-checking, and self-verification. The link condition is continuously monitored based on information about data transfer so that certain network parameters can be adjusted in order to ensure data transmission reliability as the network condition degrades. Some networks do not have a direct link between the transmitter and receiver so that data transmission must go through some nodes or repeaters. When the network degrades, certain paths along the network may be temporarily disconnected from the overall network to avoid network disruption.

The degradation mode in the canary is typically conveyed in a packet that does not carry actual data payload, and the designation is usually based on fundamental physics-of-failure concepts. Canaries can significantly reduce the uncertainties in the estimation of link conditions since each canary is tailored to a known failure mechanism to match the behavior of the functional elements such as link attenuation, depolarization, and interference that are being monitored. Canaries can be calibrated to provide sufficient advance warning of failure, i.e. prognostic distance to enable timely adjustment of appropriate network parameters. Based on the collected operational and environmental data, the network health status can be assessed. PHM information can be used for network performance forecasting and network management and resource allocation decisions that maximize availability or some other utility function such as QoS assurance for different classes of data and scheduling.

The PoF models can be used to estimate the probable time due for a network outage. However, outdoor wireless communication systems operate in harsh environments that are often abruptly affected by unpredictable and uncontrollable phenomena [3]. Uncertainty analysis of prognostics for networks can broadly be classified into three different sources as illustrated in Fig. 4:

- Network parameter uncertainty: Increases in network utilization, burst error, buffer overflow, excessive re-transmission, packet loss, and TCP congestive collapse.
- Environmental uncertainty: Temporary path obstruction by moving objects that may cause diffraction, scattering, and multipath fading; rain and fog induced attenuation, scattering, and depolarization.
- Future usage uncertainty: network expansion may in turn increase network utilization. Other future changes may be affected by factors such as network scalability and feature enhancements that may impose higher bandwidth requirements.

PHM IMPLEMENTATION IN SUB-NETWORKS

Sub-network is the term used to describe a portion of an overall communication system that consists of different interconnected networks. Some sub-networks may each contain a number of different sub-networks. For example, each paramedic, carrying a number of wearable devices, may be served by a body area network (BAN) which can be an IEEE 802.15 Bluetooth network. A group of several paramedics may work around an ambulance that operates an IEEE 802.11 wireless LAN that interconnects the nearby BANs together and relay data across an IEEE 802.16 WiMAX link that serves as the backbone of the wireless telemedicine network.

Implementing an effective PHM strategy for an entire telemedicine system requires integration of different prognostic and health monitoring approaches. The first step in implementation of prognostics is to determine the weak link in the system.

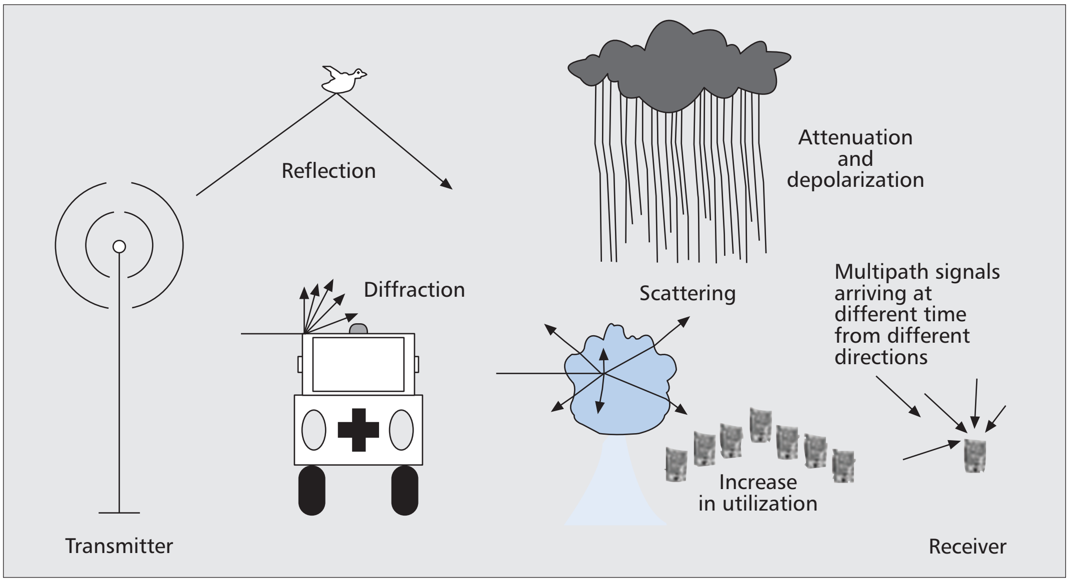

Figure 4. *Uncontrollable factors causing uncertainties.*

Fig. 5 shows the network architecture of an example in which a telemedicine network supports paramedics attending an accident scene, and each paramedic carries a number of devices supported by a BAN. In this scenario, the LAN that links these BANs consists of several sub-networks. This LAN itself is also a sub-network of the telemedicine network. In this network, many independent sub-networks are interconnected such that the individual functions of the sub-networks are combined to achieve a capability/function beyond the capability of the individual sub-networks.

Implementing an effective PHM strategy for an entire telemedicine system requires integration of different prognostic and health monitoring approaches. The first step in implementation of prognostics is to determine the weak link in the system. This can be accomplished by conducting a failure mode analysis. Once the potential failure modes, mechanisms, and effects have been identified, a combination of canaries, precursor reasoning, and environmental modeling may be implemented for different sub-networks based on their failure attributes, where each may operate under different conditions.

Different data analysis approaches such as data-driven models or PoF-based models can be used to conduct analysis of the data related to network performance. For example, attributes of the network backbone may include the path length and the number of intermediate nodes since the backbone is not necessarily a direct line-of-sight link. Prognostics rely on precipitation, noise, and interference data to be used in conjunction with environmental models to compute the susceptibility to link outage between the hospital and the ambulance. Also, statistical information about rain induced attenuation can be used to build a statistical model that is based on the correlations between these parameters. This data-driven model can be appropriately trained to detect link degradation due to attenuation and depolarization. When a sub-network fails, data packets are re-routed based on known information about the network condition and the location of the failed sub-network. Packets that experience abnormal delay or loss and have gone through a certain route would indicate that the route concerned is no longer reliable, and hence no more packets should be routed though the failed sub-network. The lost packets may need to be re-transmitted through other routes.

The major challenges in PHM implementation for a network composed of sub-networks include decisions on which sub-networks or nodes within the network to monitor and which network parameters to monitor. Another important challenge is to understand how failures in one sub-network affect another sub-network within the system and how they affect the functioning of the overall system. For example, failure of the ambulance LAN in Fig. 5 may cut off all nearby BANs. PHM for the network backbone may have different requirements as the network backbone can be either a direct line-of-sight radio link or a multi-hop network of vast coverage. In networks where a point-to-point link is insufficient, hub placement is also an important consideration to ensure maximum network reliability. Infrastructure cost and coverage will decrease with increased hub spacing, and thus there is an economic tradeoff to be considered. PHM can be adopted with information about usage and data traffic of each hub. Condition-based network monitoring also allows control of sector-to-sector interference with frequency diversity and spatial diversity which enables high frequency reuse. This would eliminate the requirement for media access control (MAC), thus saving overhead for improved bandwidth efficiency.

CONCLUSION

With advances in multimedia technology, more life-saving telemedicine applications with very stringent reliability requirements have been deployed in different areas of the world where the operating environments can vary significantly. Network reliability has very significant impli-

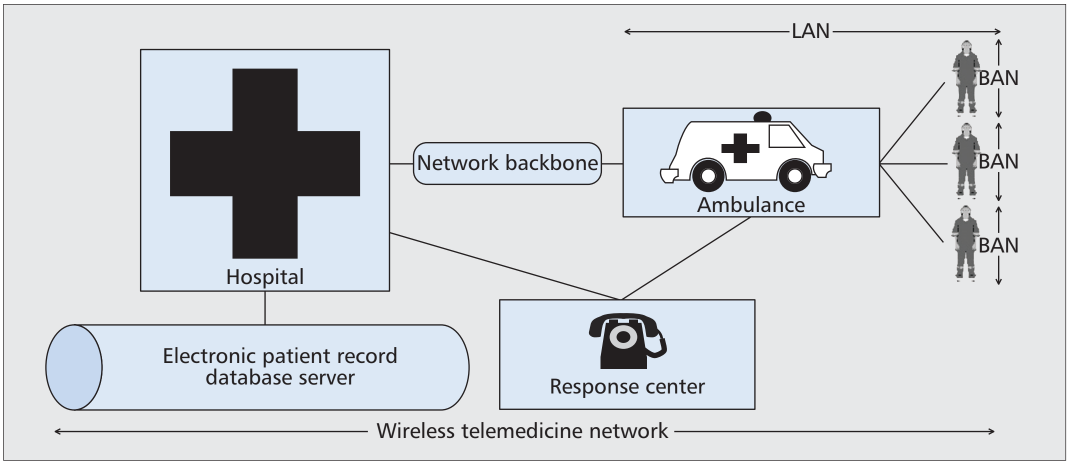

Figure 5. *Wireless telemedicine network for on-scene recovery.*

cations on these systems' operation. Through understanding of various major factors that affect the reliability of wireless communication networks, various PHM techniques can be applied to wireless communication networks in response to factors that affect the reliability. Important parameters such as network availability and data throughput can be optimized. One of the major objectives of PHM is condition-based fault management. Detection of a fault is usually accomplished when a certain network performance metric falls below its pre-determined threshold. Fault management entails symptom detection followed by problem isolation. Diagnostics can attempt to fix a problem depending on the nature of the problem. Wireless networks for telemedicine applications requiring at least 99.999 percent availability would need high resolution planning. Prognostics and health management techniques provide a cost-effective solution for the reliability prediction of wireless communication networks through condition-based optimization of various network parameters such as system link margin, dynamic routing, and power control. It is also possible to balance between network performance and reliability through best possible utilization of network resources.

Prognostics and health management techniques provide a cost-effective solution for the reliability prediction of wireless communication networks through condition-based optimization of various network parameters such as system link margin, dynamic routing, and power control.

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BIOGRAPHIES

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