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Hybrid Ultrasonic and Wireless Networks for Naval Control Applications

Abstract

The Navy has shown interest in wireless networks that distribute control data for vital ship operations. The reliability of these wireless control networks is reduced by metal bulkheads that create a challenging radio frequency propagation environment. We propose to employ the 802.15.4/ZigBee networking protocol for this task and augment it with ultrasonic data repeaters that relay control data through metal obstructions. These repeaters increase network connectivity and improve the reliability and robustness of shipboard control systems without damaging the structural integrity of the metal walls. Furthermore the ZigBee wireless network protocol admits several features that improve network reliability and information security. We describe the network architecture and show results from physical emulations of the ship's RF channels.

Introduction

Current control and telemetry networks on naval vessels use copper wires and optical cables for transmission of data across the ship. While these technologies provide full functionality and a reasonable level of security, they suffer from several deficiencies, including: i.) high installation and maintenance costs; ii.) vulnerability to a single point-of-failure if a trunk of wires were to be damaged; and iii.) structural compromise of water tight compartments for cabling.

A fully wireless solution would solve many of the problems found in a hardwired configuration, because wireless networks can be scaled, re-located and re-arranged more easily and cost effectively. This solution also provides a distributed configuration that makes the network more resilient to a single-point-of-failure. However, technical challenges exist in implementing a wireless control network on board navy ships. The use of radio frequency (RF) signals on board ships is made difficult by the severe interference created by other ship systems (e.g., radar, communication systems, and spurious device emissions). In addition, the ship's bulkheads are made entirely of metal that RF signals cannot penetrate. RF signals in one compartment cannot propagate to the next compartment without severe attenuation, resulting in network discontinuities throughout the ship. To alleviate these network discontinuities, ultrasonic data repeaters are proposed to forward baseband data through metal obstacles.

This paper describes an integrated system for distributing control data throughout a ship. The system provides networking connectivity using the IEEE 802.15.4/ZigBee wireless protocol. Network connectivity between RF-isolated compartments is accomplished with a custom Through The Bulkhead Repeater (TTBR). The TTBRs performs the following operations: 1) receive RF control data via ZigBee; 2) use ultrasonic signals to transmit the data through a metal partition; and 3) regenerate RF ZigBee packets on the other side of the partition.

System Overview

NAVAL CONTROL SYSTEM REQUIREMENTS

control systems rely on distributed control networks for the purposes of maintaining vital ship systems such as environmental sensors, damage control systems, integrated power systems, condition-based maintenance and automated logistics. The navy relies on distributed networks to provide survivability and robust control of these systems. The nature of these control messages is such that data rates are not required to be as high as typical information networks but stricter restrictions are placed on latency. These are imposed in order to keep the control system responsive to sudden changes in the environment. In addition, emphasis must be placed on the reliability of the network, to insure that vital ship processes are consistently maintained in spite of changes in the RF environment, the physical state of the network and the power supply. The machinery control information is passed through many devices across the ship. The network must thus be capable of scaling up to several hundred nodes over distances of up to several hundred feet. In addition, message security is important in ensuring that these vital control messages cannot be jammed or intercepted.

CURRENT SYSTEM ARCHITECTURE

Currently many US Naval control systems make use of the ANSI/EIA 709.1 Control Networking Standard also known as Lonworks. The Lonworks protocol is a distributed hardwired control protocol (Echelon 1999). It is capable of managing approximately 32,000 nodes in a single network domain. The protocol can operate at data rates between 10 kbps and 1.25 Mbps, and is capable of transmitting over distances between 100 meters and 6000 meters. Lonworks is capable of operating in a number of network topologies including bus, star, loop and mixed topologies. A hierarchy of device addressing, similar to that of TCP/IP, allows for reconfiguration of network routing in the event of device or link failure. The network can make use of either twisted network pairs or transmission lines for communicating data throughout the ship. Metal holes are drilled in the walls to allow for the wires and cables to pass from ship end to ship end. A diagram of a typical current hardwired control system is provided in figure 1.

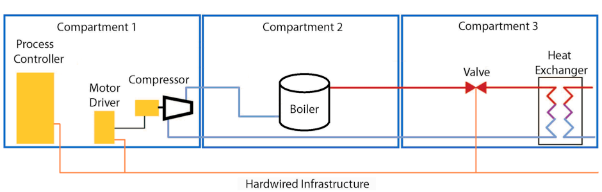


FIGURE 1. Current Network Topology

PROPOSED SYSTEM OVERVIEW

Our proposed system is designed to be a wireless equivalent of the current hardwired solutions. The network makes use of the ZigBee wireless protocol designed to operate on the IEEE 802.15.4 standard and is designed to manage up to 65,000 wireless nodes over a distance of several hundred feet. In addition, ZigBee accommodates AES encryption for secure data transmission. To improve network connectivity, transparent ultrasonic transducers are interfaced to the ZigBee protocol stack to allow seamless data transmission throughout the ship. The fully connected network allows for the implementation of a mesh topology that provides redundant route paths for data transmission and therefore increased reliability. A diagram of what the network might look like with the proposed configuration can be seen in figure 2.

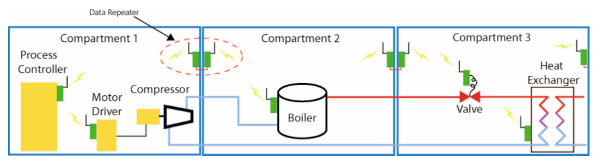


FIGURE 2. Proposed Network Architecture

Technical Considerations

technical considerations need to be addressed to ensure that the wireless network adequately performs to the specifications of the current wired network. The presence of metal walls creates a challenge to the transmission of RF signals that can be overcome with the implementation of ultrasound data repeaters. However, to ensure that the TTBRs remain transparent to the ZigBee network, it is necessary to make sure that the ultrasonic data link matches the data rates used in the ZigBee protocol. It is also important that the TTBRs reduce data latency to minimize the likelihood of dropped packets and routing bottlenecks in the network. In addition, the repeaters should handle network addresses properly so that data may be transmitted from a source device to an intended target reliably. Finally, the nature of communications for military applications requires message security. The network must provide effective protective measures against message interception.

For the implementation of the TTBR, ultrasonic energy is an ideal signal carrier, because it propagates very well through rigid materials, such as metal (Kinsler 2000). Ultrasonic transducers already exist and are currently used in industrial applications for non-destructive material strength testing. With modifications it is possible to incorporate these devices into a wireless network for the purposes of communicating between ship compartments. To facilitate the transition between the two transmission modes, an interface is necessary to allow seamless integration of the ultrasonic communications channel and the wireless networking protocol.

In order to provide connectivity, the network interface must be capable of incorporating the new physical layer extension provided by the ultrasonic transceivers without any modifications to the existing wireless protocol. This seamless integration will allow for interoperability of the TTBRs with commercial-off-the-shelf technology using the ZigBee protocol.

Since the use of ultrasonic energy for communication is relatively undeveloped and the transducers themselves are not tailored specifically for the purpose of communications, it is necessary for the interface to be capable of handling all necessary functions for the new physical layer. The interface must be capable of i.) matching the data rates between the wireless networking protocol and the ultrasonic transducers, ii.) determining the modulation techniques used in the data transmission, iii.) generating the excitation pulse for the ultrasonic transducers, and iv.) receiving the transmitted waveform and properly decoding the signal.

This paper will now describe how to develop an ultrasonic interface that adequately performs all of the above functions. The ultrasound-augmented ZigBee control network solution will also be described in detail.

Ultrasound Communication

ULTRASOUND SYSTEM OVERVIEW

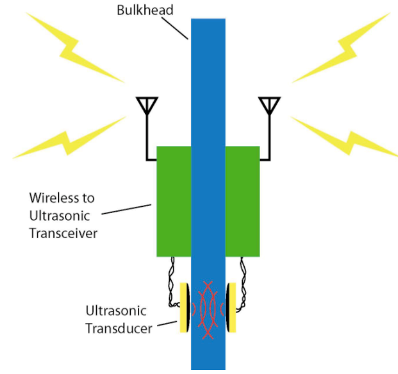


FIGURE 3. Ultrasonic Data Repeater

A diagram of the TTBR for ultrasonic communication is shown in figure 3. The ultrasonic system makes use of Panametrics NDT transducers (Panametrics) for ultrasound wave transmission and reception. The communication system is designed specifically for transmission through mild steel on the order of fractions of an inch. The ultrasonic transducers are located opposite to each other on each side of the bulkhead. The transmitting transducer is connected to an ultrasonic interface circuit. The design of the circuit is shown in figure 4.

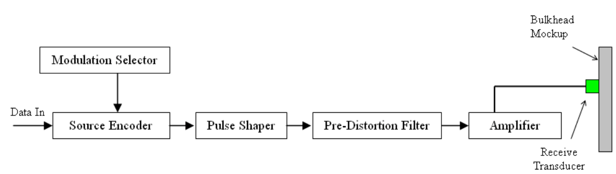


FIGURE 4. Ultrasound Transmitter Circuitry

Data obtained from a ZigBee networking protocol packet is the input to the transmitter circuitry. The data goes through pulse shaping, a pre-distortion filter, and amplification prior to transmission through the bulkhead. The pre-distortion filter, which will be described in greater detail later, is used to alleviate inter-symbol interference caused by echoes within the metal propagation channel.

The receiver on the opposite side of the bulkhead is shown in figure 5.

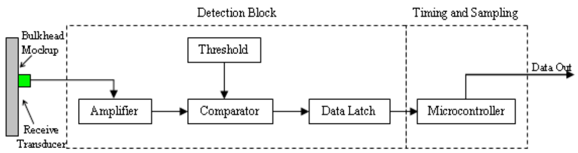


FIGURE 5. Ultrasound Receiver Circuitry

The receiver decodes the incident ultrasonic signal and extracts the payload control data. Due to the use of the pre-distortion filter at the transmitter, this receiver structure is relatively simple. Specifically, it does not require a matched filter or computationally intensive equalization and instead only consists of a threshold comparator. The output data from the TTBR is then sent to a ZigBee protocol transmitter for wireless RF re-transmission.

TRANSMISSION PARAMETERS

CHANNEL CHARACTERIZATION

The driving signal for the transducers is a rectangular pulse signal. The amplitude of the pulse is roughly 5 V to keep the transducers operating within linear operating regions (Panametrics). The transducers are excited on the rising and falling edge of the pulse and as such the width of the pulse is chosen to be 73 ns in width. This width corresponds to the resonant frequency of the sound wave being created and is chosen to optimize the ringing amplitude at the transmitter. Figure 6 shows the received waveform after the transmitter is struck with a single pulse.

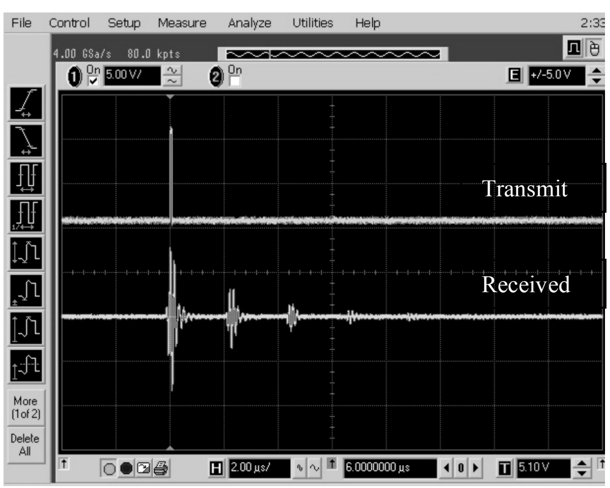


FIGURE 6. Received Waveform from Transmitted Pulse

The upper trace is the signal used to excite the transmitting transducer as described above and the lower trace is the waveform captured by the receiving transducer. Several phenomena are observed in the received signal. Figure 6 shows that the transducer itself acts a bandpass filter with a center frequency of approximately 6.8 MHz. This filtering occurs due to the fact that the transducer makes use of piezo-electric ceramics that behave electrically as capacitors. The piezo-ceramics oscillate mechanically when a voltage is applied across them. When paired with an inductor, the circuit behaves electronically like a simple oscillator. The result is the generation of narrow band waveform. The wave decays exponentially with a rate determined by the intrinsic properties of the metal that the wave is passing through. In addition to the decay of the ultrasound wave, the presence of decaying echoes can also be seen in the ultrasonic channel. The echoes correspond to a mismatch in acoustic impedance at the surface where the transducers mate with the bulkhead (Kinsler). As the wave encounters the interface, a portion of the energy is transmitted to the transducer while the remaining energy is reflected back in to the bulkhead. This energy travels back and forth within the bulkhead manifesting as a number of echoes apparent at the receiver. A block diagram of the channel model can be seen in figure 7 where both $T_1(s)$ and $T_2(s)$ model the transmit and receive transducers respectively and the bulkhead is modeled as $B(s)$.

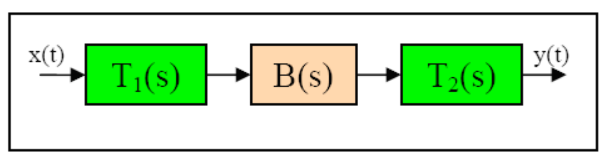


FIGURE 7. Block Diagram of Ultrasound Channel

From figure 6 it can be seen that the echoes increase the amount of time required for the first pulse to dissipate before a second pulse could be generated without inter-symbol interference (ISI). ISI. This severely limits the raw data rate achievable through the bulkhead. Using the channel model shown in figure 7, the next section describes a technique for mitigating ISI.

PRE-DISTORTION FILTERING

As seen in the previous section, the presence of the bulkhead in the communication channel creates echoes that severely distort the received waveform and can limit the data rate of the channel. The effects of these echoes can be mitigated by the use of digital signal processing but, techniques such as these increase system complexity and result in increased power consumption which limits the battery life of stand-alone nodes. To avoid this complex processing, a pre-distortion filter has been designed. The pre-distortion filter is designed based on two assumptions about the channel.

- Assumption 1: Each echo is a scaled and shifted copy of the originally transmitted pulse
- Assumption 2: The echoes decay such that:
  $Amp[e_{i+1}(t)] = \alpha \cdot Amp[e_i(t)],\ 0 < \alpha < 1$

These assumptions allow the channel to be modeled as a dispersionless transmission line (Pozar 2005). Thus, the system can be seen as three cascaded linear time invariant systems and the channel described in figure 7 can be re-arranged as shown in figure 8.

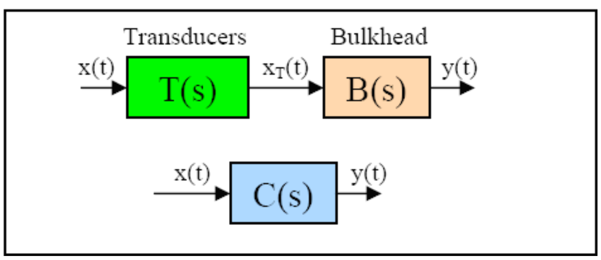


FIGURE 8. Revised Ultrasonic Channel model

Using this channel model, the goal is to develop a pre-distortion filter (shown in figure 9) that dampens the echoes generated as a result of the presence of the bulkhead in the channel.

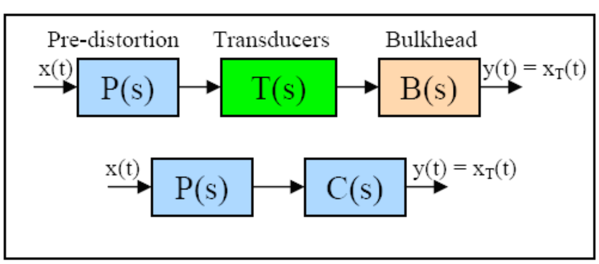


FIGURE 9. Desired Channel Response

Using Assumptions 1 and 2 above, the impulse response of the bulkhead can be modeled as:

$$h_B(t) = \sum_{n=0}^{\infty} \delta(t-(1+2n)t_T)\alpha^{1+2n} \qquad (1)$$

where: t_T = transit time of acoustic signal in bulkhead
α = channel attenuation constant ($0 < \alpha < 1$).

This equation shows that the bulkhead channel is modeled as a series of decaying impulses delayed in time. The impulse response of the entire channel can then be modeled by equation 2.

$$\begin{aligned} h_C(t) &= h_T(t) * h_B(t) \\ &= \sum_{n=0}^{\infty} h_T(t-(1+2n)t_T)\alpha^{1+2n} \qquad (2) \end{aligned}$$

It can be noted from equation (1) that the bulkhead response can be modeled as an exponentially weighted moving average cascaded filter with a time delay of t_T. This filter has an inverse response as described by equation (3)

$$h_P(t) = \delta(t) - \alpha^2 \cdot \delta(t-2t_T) \qquad (3)$$

Using equation (3) as the impulse response of the pre-distortion filter, the resulting channel response can be calculated as follows

$$\begin{aligned} h(t) &= h_P(t) * h_C(t) \\ &= \sum_{n=0}^{\infty}\left[h_T(t-(1+2n)t_T) - \alpha^2 \cdot h_T((t-(1+2n)t_T)-2t_T)\right]\alpha^{1+2n} \\ &= \sum_{n=0}^{\infty} h_T(t-t_T-2t_T n)\alpha^{1+2n} - \sum_{n=0}^{\infty} h_T(t-t_T-2t_T(1+n))\alpha^{1+2(1+n)} \\ &= \alpha \cdot h_T(t-t_T) + \sum_{n=1}^{\infty} h_T(t-t_T-2t_T n)\alpha^{1+2n} - \sum_{n=1}^{\infty} h_T(t-t_T-2t_T n)\alpha^{1+2n} \\ &= \alpha \cdot h_T(t-t_T) \qquad (4) \end{aligned}$$

Equation (4) shows that the pre-distortion filter has the intended effect of suppressing the echoes at the system output. Implementation of the pre-distortion filter amounts to taking each transmitted pulse and following it with a time delayed, amplitude scaled version of itself. When properly designed, this “canceling” pulse causes destructive interference in the bulkhead, attenuating the echoes. The effect of this cancellation pulse can be seen in figure 10.

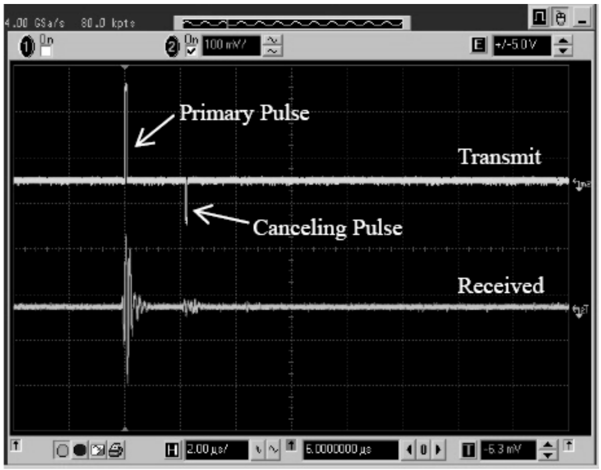
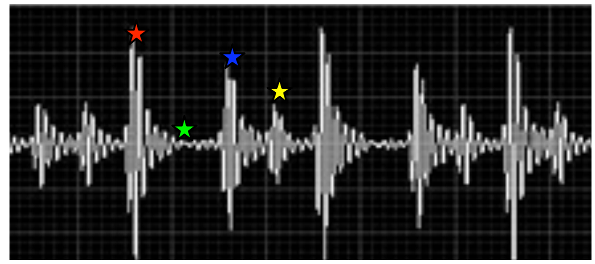


FIGURE 10. Effect of Pre-Distortion Filter

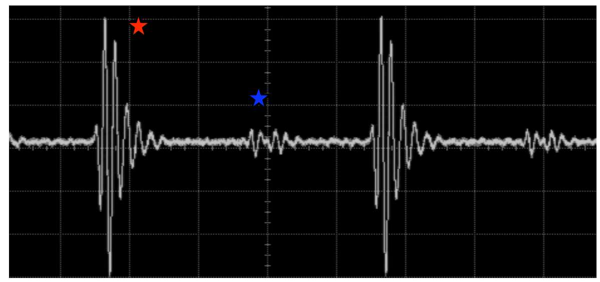
Figure 10 shows that the distortion filter does not result in complete cancellation of the echoes but rather mitigates their effect to a level that is manageable by the system. This is mostly likely due to the assumptions made about the channel response to simplify the channel model. A more accurate model of the channel impulse response could allow for more complete cancellation of channel echoes.

DATA RATE ADAPTATION

With the use of the pre-distortion filter it is possible to achieve raw symbol rates on the order of 1 Msymbols/s, approximately 4 times faster than without pre-distortion. In addition to increasing the raw symbol rate, the data rate can be increased by using alternative methods of signal modulation. Using 4-ary Amplitude Shift Keying (ASK), the transmitter can generate pulses of 4 unique discrete amplitudes. Each of these amplitudes represents two bits of data, effectively doubling the rate of data. This data rate doubling is possible because of the effective lack of additive noise in the channel that can contribute to ambiguity in estimating the received signal. As shown in figure 11a, four different amplitudes can be easily identified above the noise floor. If power conservation is required, or the channel changes substantially enough that the data rate may not be maintained, the transmitter is capable of reverting to low data rate operation via On Off Keying (OOK) as seen in figure 11b.



(A)



(B)

FIGURE 11. A.)ASK Modulated Signal B.)OOK Modulated Signal

ULTRASOUND COMMUNICATION PERFORMANCE

The ultrasound communication link is capable of transmitting data at rates of up to 2 Mbps. If both ends of the ultrasonic link share the channel for bidirectional communication, this would allow for one way raw data rates of approximately 1 Mbps. In addition, training data for the pre-distortion filter is not frequently required due to the static nature of the acoustic channel. Since this is the case, the ultrasound communication link is capable of matching the required data rates as set in the ZigBee wireless protocol that it must interface with. The low level of thermal noise in the acoustic channel is due to the fact that very few mechanical oscillations occur naturally at frequencies on the order of 6.8 MHz. The result of these lack of oscillations is a smaller noise variance which in turn results in a lower bit error rate (Haykin 2000).

RF Communication

THE ZIGBEE WIRELESS PROTOCOL

The ZigBee wireless protocol is built on the IEEE 802.15.4 standard, and differs from the IEEE

802.11 and Bluetooth standards in that its design is better suited to control and sensor networks that rely on low power consumption and require lower data rates (ZigBee 2005). Low power consumption is necessary because the ships that make use of these networks will be at sea for months at a time and may require stand alone support from the sensor network without frequent battery replacement. The ZigBee stack is capable of managing up to 65,000 nodes and each node is capable of transmitting over 75 meters (ZigBee 2005). The physical layer is designed to operate in the 900 MHz or 2.4 GHz band with data rates of up to 250 kbps. These specifications are roughly on the order needed for maintaining a ship-wide network and managing the necessary devices for machine controls on board the ship. Also, ZigBee uses direct sequence spread spectrum (DSSS) modulation and has built-in encryption for added security (ZigBee 2005). These features make ZigBee ideal for naval applications where information security and resistance to signal jamming are necessary.

NETWORK TOPOLOGY

The ZigBee protocol is capable of maintaining three different types of network topology (ZigBee 2005). The star topology makes use of a single parent node to route all data from one end user to another. This architecture is the most simplistic and therefore easiest to implement. It is however, vulnerable to a single point of failure in that if the parent node were to fail, the end user nodes would not be able to communicate with each other. Since reliability is vital in these control networks, this vulnerability is unacceptable. The cluster tree topology allows the use of second tier routers to route data from the end user to the parent node and vice versa. In this configuration, the second tier nodes are able to manage sub-clusters of the network and provide limited communication in the event of failure of the parent node. This helps avoid the problem of a single point of failure but failure of a crucial node still results in severely limited connectivity of the network. The mesh topology allows second tier devices to route not only from the end user to the parent node but also to other second tier routers. This configuration allows for redundant route paths whereby if one second tier or parent node fails the network is capable of maintaining manageable levels of network connectivity by use of alternative route paths. For this reason the mesh topology is ideal for use in this network as it provides the most reliable network connectivity in the event of node failure. An example of a ZigBee mesh network topology can be seen in figure 12. The network is composed of Full-Function Devices (FFD), which require more memory and are capable of routing and managing a network, and Reduced-Function Devices (RFD), which use less power but may only communicate directly with a FFD acting as a coordinator or a router. Therefore, RFDs are used as ZigBee End Devices, while a FFD may act as either a ZigBee Coordinator or a ZigBee Router. The role of the coordinator is to initialize the network, store information about the other nodes in the network, and assign addresses to all devices in the network. Multiple mesh networks with multiple coordinators can be linked together through a wired interface, called a ZigBee Extension Device, to form larger networks or to transfer data to a network using IP.

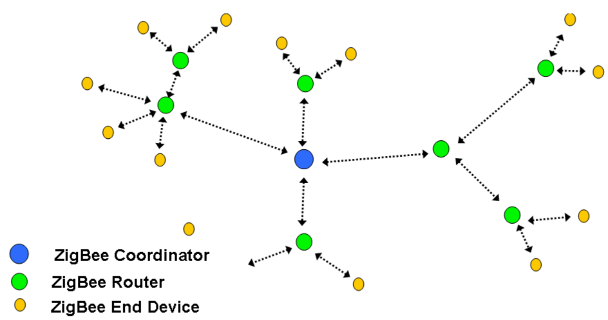


Figure 12. ZigBee Mesh Topology

PROTOCOL STACK MODIFICATION

An example ZigBee protocol stack organization is shown in figure 13. The application layers serve to manage services (e.g. temperature readings) with devices that require the information (e.g. a thermostat). The network layer is responsible for routing, link status updates, etc. The IEEE 802.15.4 standard defines the MAC and physical layers. In order to permit a ZigBee network to operate between compartments, however, this stack organization must be modified so that it can transfer data and routing information through the ultrasound channel.

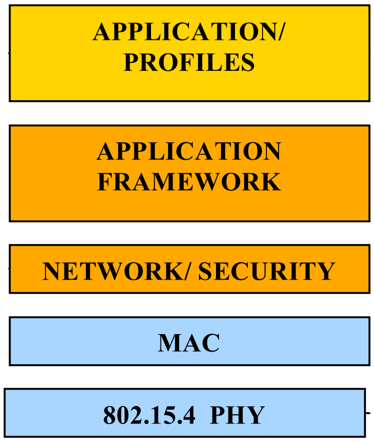


FIGURE 13. ZigBee Protocol Stack

A revised protocol stack is shown in figure 14; this revised stack is only used in devices that act as a TTBR. Here an additional section to the physical layer is included below the MAC layer so that data can be routed as needed through a serial interface instead of to the radio. If a packet that is sent from the application layer or routed through the network layer is designated for a device on the other side of the wall, the packet is sent out the serial interface. The serial output communicates directly with the interface to the ultrasound channel. On the other side of the ultrasound channel, the packet is received by the serial interface and passed up to the MAC layer.

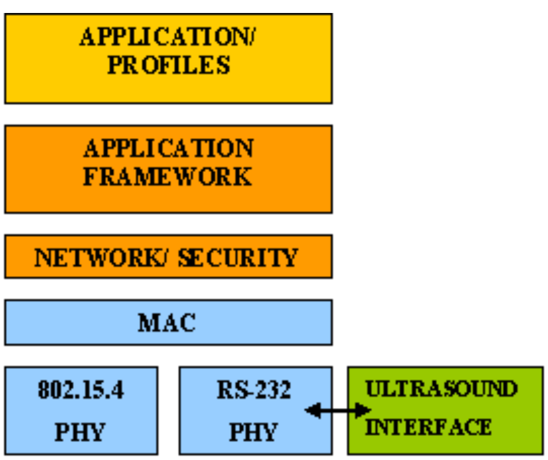


Figure 14. Revised Networking Protocol Stack with Ultrasound Interface

RF COMMUNICATION PERFORMANCE

In addition to the reliability of the wireless network built in to the ZigBee protocol, a number of modifications have made the device more reliable and rugged in severe environments. Encryption and DSSS increase the signal security and help protect against unwanted detection. ZigBee's use of mesh network topology helps prevent against vulnerability to a single point of failure whether that be a bottleneck in data routing or the complete failure of a node. Beyond that, a number of modifications have been made to adapt the commercial standard to use aboard naval ships.

Conclusions

We have selected the IEEE 802.15.4/ZigBee wireless protocol for maintenance of large-scale control processes. ZigBee's low power operation allows for stand-alone network survivability over long periods of time using only battery power. Built-in security features provide increased data security to protect vital information from unwanted identification.

However, the ZigBee network, or any other conventional wireless network, is of limited use aboard naval ships. The reason is the harsh RF environment, and the metal walls that impede the transmission of RF signals. To address these challenges, ,a number of modifications to the wireless network have been recommended. The most important one is the use of ultrasonic communication for seamless transmission of control signals through metal walls. This technique assures connectivity among disjoint compartments of the ship without impediment to the structural integrity of the hull. The approach was demonstrated experimentally in physical environments that emulate metal obstacles on US Navy ships.

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