Simulation of Underwater Acoustic Networks with Field Measurements

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***Abstract*—Due to both logistical and technical difficulties of deploying realistic underwater acoustic networks, research involving underwater networks has primarily been limited to either theoretical analysis or simulation study. For simulation, however, there exist few commonly accepted acoustic channel models, which makes simulation study less realistic. The Kauai Acomms MURI 2008 (KAM08) experiment was conducted near Hawaii in Summer 2008, which provided us with first-hand, physical measurements of realistic acoustic communications. The paper describes how the measurements of the KAM08 experiment were programmed into a custom acoustic channel model for the QualNet simulator. We also simulated a underwater networking scenario that used an adaptive modulation scheme to optimize the energy efficiency so as to demonstrate the utility of the custom acoustic channel model.**

I. Introduction

The performance of underwater acoustic networks (UWANs) suffers from limited bandwidth and fast channel fluctuation, which severely limit the capacity of acoustic communications. Extensive research has been conducted in recent years to address different issues in UWANs (*e.g.*, see [1], [2], [3], [4], [5], [6] and references therein). However, due to both logistical and technical difficulties of deploying UWANs for realistic scenarios, research involving UWANs has primarily been limited to either theoretical analysis or simulation study. For simulation, in particular, there exist few commonly accepted acoustic channel models, which makes simulation study less realistic.

During the months of June and July in 2008, the Kauai Acomms MURI 2008 (KAM08) experiment was conducted near the Kauai Island, Hawaii [7]. In the KAM08 experiment, extensive acoustic communications were conducted by two source array transmitters and three vertical line array receivers while the ocean environment was being monitored. These experiments provided us with first-hand, physical measurements of realistic acoustic communications.

In this paper, we describe how the physical measurements conducted by the KAM08 experiment have been programmed into a custom acoustic channel simulation model for the QualNet [8] network simulator. To demonstrate the utility of the custom acoustic channel model, we design a networking scenario that utilizes an adaptive modulation scheme to optimize the *energy efficiency* defined as the ratio of the total number of data bits received successfully to total energy used for transmission.

QualNet uses a layered architecture similar to that of the TCP/IP network protocol stack. Within that architecture, data moves between adjacent layers. QualNet's protocol stack consists of, from top to bottom, the Application, Transport, Network, Link (MAC) and Physical Layers. In the context of underwater acoustic networks, the Physical Layer is responsible for transmitting and receiving raw bits from the underwater acoustic channel. At the source node, the Physical Layer receives data from the Link (MAC) Layer and sends the data to the Physical Layer of the destination node. At the destination node, the Physical Layer receives data from the Physical Layer of the source node and passes the data to the Link (MAC) Layer. The underwater acoustic channel transmits signals between nodes, and interfaces with the Physical Layer entities at the nodes. An acoustic channel model in QualNet simulates the propagation of signals between nodes, taking into account both propagation delays and signal attenuation due to path loss, fading, and shadowing. Due to the lack of commonly accepted acoustic channel models, we programmed the measurements of the KAM08 experiment into a custom acoustic channel simulation model.

The remainder of the paper is organized as follows. we first review the KAM08 experiment in the next section. In Section III, we illustrate how the KAM08 measurements of realistic acoustic communications have been incorporated into the QualNet network simulator to serve as an acoustic channel simulation model. In Section IV, we describe a scenario of UWAN, which uses the KAM08-based acoustic channel simulation model to evaluate an adaptive modulation scheme accommodating the fluctuating acoustic channel condition and optimizing the energy efficiency of the simulated UWAN. Section VI concludes the paper.

II. Reviw of the KAM08 Experiment

The KAM08 experiment was conducted in the summer of 2008 at a 100-meter shallow water site west off the Kauai Island, Hawaii. Fig. 1 depicts a partial configuration of the KAM08 experiment for a 35-hour period from JD180 (June

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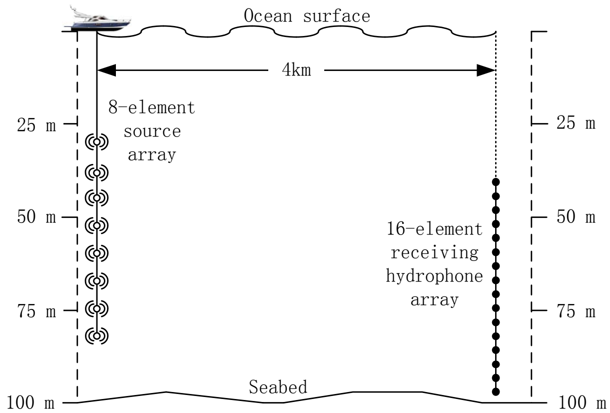


Fig. 1. Partial configuration of the KAM08 experiment.

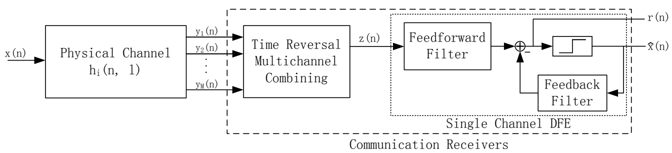


Fig. 2. Block diagram for acoustic measurement and data processing.

28) 05:00 to JD181 (June 29) 16:00. During this period, a 8-element source array was deployed off the R/V Melville, and the source level of each element was 185 dB re 1 μPa at 1 m. The 8 elements of the source array transmitted 30-second long BPSK signals in a round robin fashion. The transmissions were repeated every 30 minutes for 35 hours. The carrier frequency of BPSK signals was f_c = 15 kHz and the symbol rate was R = 5 kilosymbols/sec. At 4 km away from the source array, a 16-element vertical line receiving array was deployed to measure the propagated acoustic signals, where each element is a receiving hydrophone to measure the received signals. The element spacing of the receiving array was 3.75 m and its aperture was 56.25 m covering water depth from 42 m to 98.25 m. Then the measurement of the propagated and received signals were processed off-line by the time reversal receiver described in [9].

Fig. 2 depicts the functional block diagram for the acoustic measurements and data processing. Communication symbols $x(n)$ were transmitted from the source. The propagated acoustic signals were measured at the multiple receiving hydrophones. So the received signal at the i^{th} hydrophones can be represented as

$$y_i(n) = x(n) \circledast h_i(n, l) + v_i(n) \tag{1}$$

in the discrete baseband, where $\circledast$ denotes the convolution operation, $v_i(n)$ represents the ambient noise, and $h_i(n, l)$ denotes the time-varying, multi-path underwater acoustic channel.

The receiver consists of time reversal combining and subsequent single channel decision feedback equalizer (DFE). Phase tracking and frequent channel estimation are used to combat channel fluctuations in dynamic ocean environments. With channel estimates, the received signals from multiple

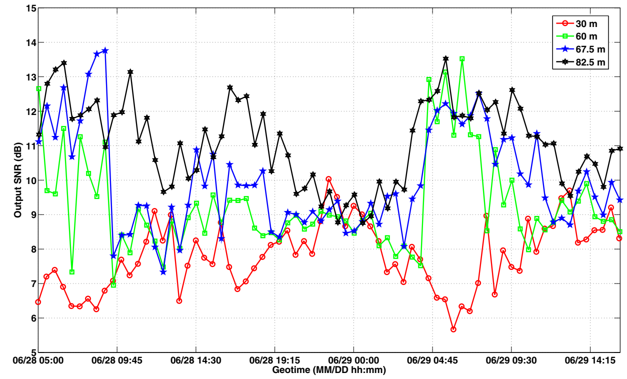


Fig. 3. Output SNR corresponding to 4 source array elements at different depths in KAM08.

hydrophones are matched-filtered and the results are combined into a single composite signal $z(n)$. Then DFE compensates for the inter-symbol interference in $z(n)$. $r(n)$ is the soft output of the DFE and $\hat{x}(n)$ is the hard decision results.

Communications data from 8 elements of the receiving array were processed by the time reversal algorithm. In processing of the 35-hour communications data, the time reversal receiver used a common set of parameters. For example, in the single channel DFE, the feedforward filter span was $N_{ff} = 8$ symbols long and the decision feedback filter had $N_{fb} = 2$ taps. Fig. 3 shows the physical layer communications performance in terms of the signal-to-noise ratio (SNR) measured at the soft DFE output for four source array elements during the 35-hour period. The soft output SNRs showed significant fluctuations during the 35 hours for all four source array elements. Particularly, the middle and the bottom transmitters experienced 6-7 output SNR changes during this period. This means the acoustic channel experienced significant fluctuations because of the ocean variability. It is also noteworthy to mention that all output SNRs for the four transmitters were about 6 dB or higher. For the middle and bottom transmitters, the output SNRs were over 12 dB for some periods.

Consider the physical ocean channel and the communications receiver as an integrated physical layer subsystem with $x(n)$ as its input and $r(n)$ as its soft output. Based on the fact of high SNR DFE output and limited feedback taps in the DFE, this subsystem can be considered largely linear. Furthermore, if we model the physical layer as:

$$r(n) = x(n) + w(n), \tag{2}$$

where $w(n)$ is the noise of the physical layer, $w(n)$ is found be to independent, identically-distributed complex Gaussian. As depicted in Fig. 4, both the real part and the imaginary part of $w(n)$ match well with the probability density function (PDF) of Gaussian distribution with a near-zero mean for an example of 10 second BPSK data. Either the real part or the imaginary part of $w(n)$ is found independent in time. The conclusion that the Physical Layer noise being modeled as Additive White Gaussian Noise (AWGN) allows the derivation of bit-error-rate (BER) of data transmitted with different modulation schemes

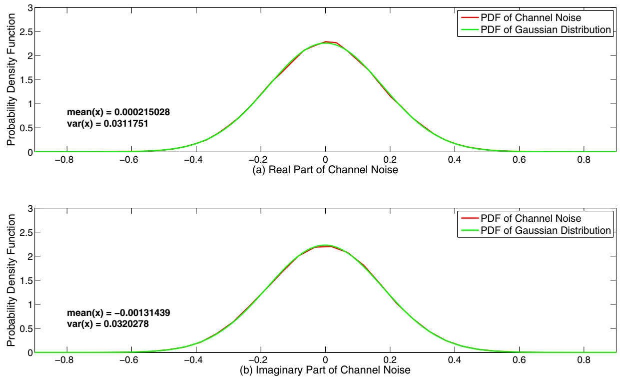


Fig. 4. Probability density function of channel noise.

based on the SNR measured from the BPSK field data in KAM08.

III. Incorporating KAM08 Measurements into QualNet Simulator

In this section, we describe how the KAM08 measurements of physical acoustic communications was incorporated into the QualNet network simulator. Fig. 5(a) depicts the conceptual architecture of QualNet extended with two functional blocks, *SNR Lookup* and *SNR-BER Converter*, together served as an acoustic channel simulation model at the physical layer.

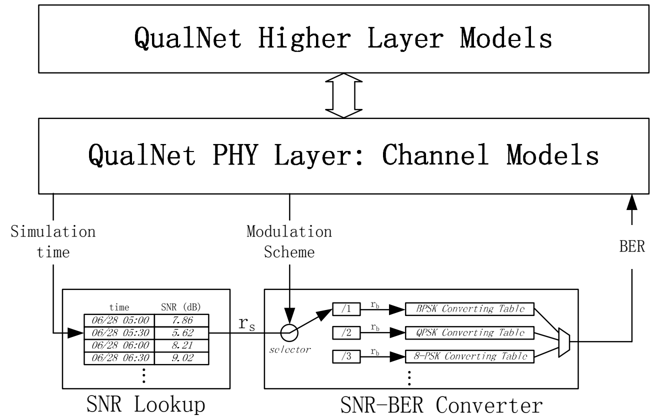
A. Functional Blocks

The SNR Lookup functional block stores KAM08-measured raw output SNR data into a table indexed by the actual occurring time instances of acoustic communications conducted in KAM08. In designing underwater networking scenarios that will be simulated with the KAM08-based channel model, we have to accommodate the fact that KAM08 acoustic communications were physically conducted and measured every 30 minutes. During simulatuon, SNR Lookup uses a given simulation time to look up the table and return the corresponding SNR.

Although SNR Lookup returns realistic SNR, such data only measures the performance of the physical acoustic communications. The SNR-BER Converter functional block converts an input SNR into bit error rate (BER) used to evaluate the link level performance. Furthermore, since noice has been validated to be AWGN based on KAM08 measurements, the raw KAM08 SNR data for acoustic communications using BPSK may also be converted into BER values for acoustic communications using QPSK and even 8-PSK as well. For these conversions, we assume the symbol length remains the same. As BPSK only encapsulates one bit in each symbol, the raw KAM08 SNR can be considered as SNR per symbol (γ_s). SNR per symbol (γ_s) is first converted into SNR per bit (γ_b) via Eq. (3) [10]:

$$\gamma_b = \gamma_s / k \tag{3}$$

where k (number of bits per symbol) is determined by the modulation scheme used (*e.g.*, $k = 1$ for BPSK and $k = 2$ for QPSK, etc.). The obtained SNR per bit is then converted into



(a) QualNet extended with KAM08-based acoustic model

```
function [ output_args ]=MpskSnrToBer(mary,
                                       snrPerSymbol)
    k = mary;
    snrPerBit = snrPerSymbol/k;

    symbolErrorRate = 0.5*erfc(sqrt(k*snrPerBit)
                      *sin(pi/2^k));
    output_args = symbolErrorRate;
```

(b) Matlab function to compute mudulation specific BER

```
BOOL PhyAcousticCheckRxPacketError()
{
    //Initialization
    …
    snr = phyAcousticRealSNR(simulationTime,
                             sendingNode,
                             receivingNode);
    BER = PHY_BER(rxModulationType, snr);
    //Proceed to calculate packet loss rate
    ...
}
```

(c) Added QualNet function to compute packet loss rate

Fig. 5. Incorporation of KAM08 into QualNet

BER for the corresponding modulation scheme using digital communication theory [10]. Such conversion was computed off-line by the Matlab function depicted in Fig. 5(b), which takes both number of bits per symbol (*mary*, indicating the modulation scheme used) and SNR per bit (*snrPerBit*) as inputs, and computes the corresponding BER as the output. The converted BER values and their corresponding modulation schemes are storeed in the SNR-BER Converter functional block.

B. QualNet Implementation

In practice, the KAM08-based acoustic channel model was implemented in QualNet as follows. Existing QualNet provides the `PHY_BER` API to perform SNR to BER conversion for RF signals. The internal data accssed by `PHY_BER` is replaced with the data stored in the SNR-BER Converter functional block to perform SNR to BER conversion for acoustic signals. The function `PhyAcousticCheckRxPacketError` (shown in Fig. 5(c)) was implemented, which is invoked for each incoming frame to compute its corresponding loss rate based on the SNR of the physical acoustic channel. During simulation, the simulation time of a packet's arrival from the physical acoustic channel at a receiver was used to index the corresponding SNR value via QualNet function `phyAcousticRealSNR`. A returned SNR value is then converted into a corresponding BER value for the modulation scheme used via QualNet function `PHY_BER`. Using the BER, QualNet proceeds to calculate the probability of packet loss and evaluates the performance of upper layer functions. In this way, the KAM08-based acoustic channel model is transparently incorporated into QualNet, and the evaluatuion of networking behavior and performance directly utilizes a realistic acoustic channel model to facilitate high fidelity simulation.

IV. Simulation of UWANs with KAM08 Measurements

To demonstrate the usage of the KAM08-based acoustic channel simulation model, we designed an underwater networking scenario where transmitters use an adaptive scheme to choose proper modulation to accommodate the fluctuating channel condition and optimize the energy efficiency. The performance of such an adaptive scheme has been evaluated via simulation with KAM08-based custom acoustic channel model.

A. Energy Efficiency

Since UWANs operate on batteries, it is paramount to conserve energy so as to maximize the network life time. One major energy drain is data transmission since acoustic communications consume a lot more energy in transmission than reception [11]. Although lowering transmission power might be an intuitive approach to conserving energy, such method may also lower both the data transmission rate (due to the need to use a lower rate modulation) and the received SNR. Lowered received SNR is prone to cause the receiver to fail to correctly receive the transmitted signals. Such reception failures waste energy and may demand retransmissions. To optimize network operations, we define the metric *energy efficiency* to be

$$\frac{\text{total number of data bits received successfully}}{\text{total energy used for transmission}}, \quad (4)$$

which takes into account both energy consumption and successful data transmissions. In a perfect channel with no reception errors, the inverse of energy efficiency gives how much energy is consumed to transmit a single bit.

B. Adaptive Modulation Scheme

Since higher rate modulation can encapsulate more bits into one symbol (*e.g.*, two bits can be encapsulated in one symbol for QPSK), under the same symbol rate, it takes less time to transmit a single data frame, which leads to less energy consumption assuming the transmission power is constant and the total energy consumption is proportional to the duration of transmission. However, higher rate modulation makes transmitted signals more susceptible to channel noise which requires higher received SNR for successful reception.

The adaptive scheme maximizes energy efficiency by choosing proper modulation according to the fluctuating channel conditions affected by surface waves, water temperature, and other factors. However, it is infeasible for transmitters to correctly predict output SNR. To address this issue, the adaptive scheme implemented a *probing* method for transmitters to measure the recent performance of the acoustic channel. Specifically, before transmitting a real data frame, a transmitter sends out a short probe message to the receiver to measure channel condition. The receiver sends back the measured received SNR in a short probe response message to the transmitter. Based on the measured received SNR, the transmitter chooses a proper modulation scheme for data frames. Both the probe message and the probe response message are modulated by BPSK to reduce the chance of failed reception.

With good channel condition, the transmitter uses higher rate modulation to reduce transmission duration. Otherwise, lower rate modulation is used to make the transmitted signals less susceptible to channel noise. Fig. 6 depicts how well (in terms of frame loss rate and energy efficiency) different modulations work (static BPSK, static QPSK, and adaptive modulation) at each time instance over the 35-hour period. Fig. 6(a) shows the measured output SNR of the signals sent by the transmitter located at 82.5 m below the sea surface. Fig. 6(b) shows the frame loss rates of the three modulation schemes. It is clear that higher loss rates were resulted from using the static QPSK scheme while the output SNR was low. Fig. 6(c) shows that the adaptive scheme always chosed the modulation that can archive higher energy efficiency. In our simulation, when the measured received SNR is higher than a threshold (which depends on the size of the data frame to be transmitted), QPSK is used to reduce transmission time. Otherwise, BPSK is used to reduce the probability of failed reception. Due to the relatively poor acoustic channel condition in KAM08 where the maximum output SNR was less than 14 dB, we only evaluate an adaptive scheme that selects between BPSK and QPSK. Such an adaptive scheme may easily incorporate other modulations such as 8-PSK and digital Pulse Amplitude Modulation (PAM) when the output SNR is even higher.

By observing both Figs. 6(b) and 6(c), we can conclude that the adaptive scheme does not simply choose modulation that minimizes the frame loss rate. Given a fixed frame size, the frame loss rate is determined by the bit error rate. To get lower frame loss rate, one should simply choose lower rate modulation which always yields better BER performance. But such scheme increases total transmission time and may consume more energy In particular, the adaptive scheme proposed here takes both energy efficiency and frame loss rate into consideration and choose higher rate modulation as it can archive similar (low) frame loss rate when the measured received SNR is high and also greatly reduce the transmission time.

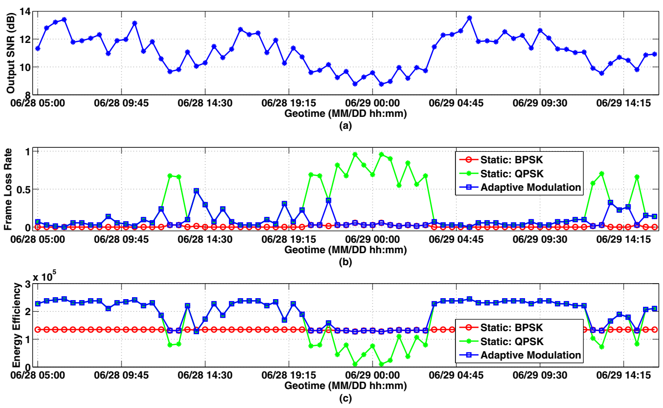


Fig. 6. Receiver performance and energy efficiency of transmitter at 82.5 m below the sea surface (MAC Layer frame size: 106 Bytes)

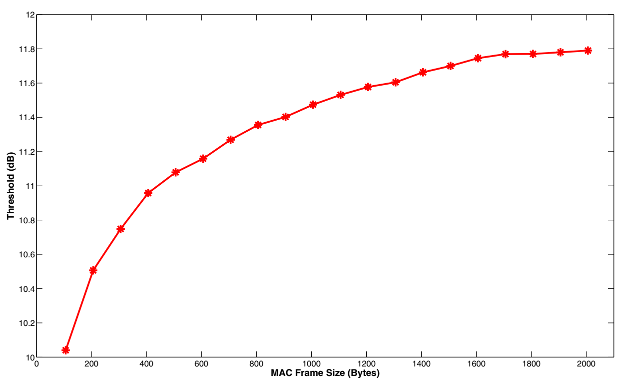


Fig. 7. Decision thresholds used for different frame sizes.

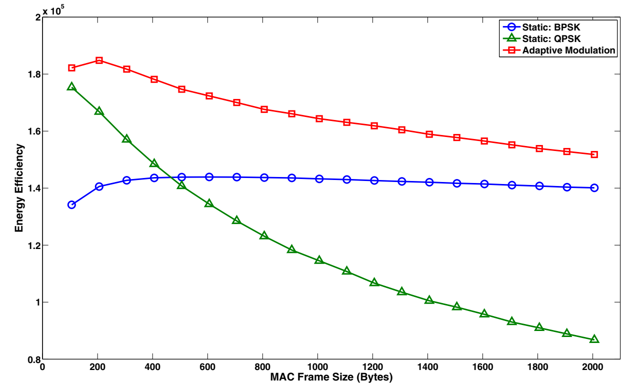


Fig. 8. Energy efficiency for different MAC frame size of transmitter at 82.5m below sea surface.

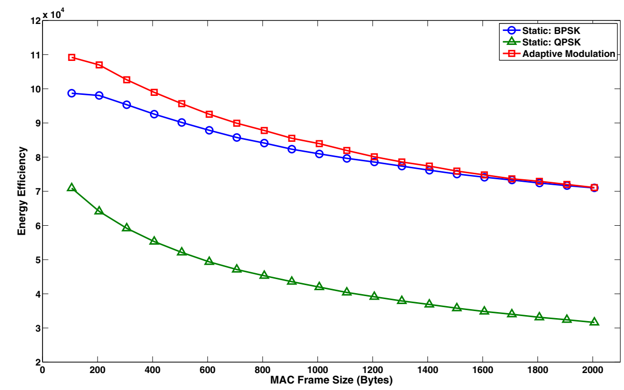


Fig. 9. Energy efficiency for different MAC frame sizes of 4 transmitters at depths of 30 m, 60 m, 67.5 m and 82.5 m below sea surface.

V. Simulation Results

We simulated a network topology mimicking the KAM08 experiment with only four transmitters located at 30 m, 60 m, 67.5 m and 82.5 m below the sea surface. The transmission patterns also mimicked the KAM08 experiment where two scenarios were simulated, (1) only one transmitter at 82.5 m below the sea surface transmitted and (2) all four transmitters transmitted in a round-robin fashion, every 30 minutes. For the adaptive scheme, the SNR thresholds used to select the proper modulation are shown in Fig. 7, which depend on frame sizes.

A. *Effects of frame size*

Fig. 8 shows the impact of frame size on energy efficiency of the transmitter at the depth of 82.5 m. Compared with the static BPSK scheme, the adaptive scheme archived an improvement in energy efficiency from 35.8% to 8.3% when the MAC layer frame size grew from 106 bytes to 2006 bytes. The reason why energy efficiency of the adaptive scheme decreases with growing frame size is two-fold. (1) With the same BER, a larger MAC frame has higher probability to be corrupted. Thus energy efficiency of the adaptive scheme decreases just like the two static modulation schemes do. (2) Larger frame sizes require better channel condition for successful reception. Given a particular output SNR, the adaptive scheme tends to choose QPSK for smaller frames but BPSK for larger frames. Thus, the performance of the adaptive scheme resembles the static BPSK scheme when the frame size grows.

We also simulated the scenario where all four transmitters transmitted and the total energy efficiency was measured, as shown in Fig. 9. The largest improvement of energy efficiency observed was around 10%. The decrease in improvement is due to the fact that some transmitters suffers from poor channel condition (Fig. 3 shows the maximum output SNR of the transmitter at depth of 30 m is less than 10 dB). In this situation, BPSK is always chosen and the adaptive scheme resembles the static BPSK scheme.

B. *Effects of channel fluctuation*

The adaptive scheme was designed to accommodate channel fluctuation. As shown in Fig. 3, the acoustic channel experienced fluctuation as much as 7 dB during the 35 hour period. In such a dynamic environment, the adaptive scheme chosed low rate modulation when the output SNR is low and switched to high rate modulation otherwise so as to improve energy efficiency. Fig. 10 shows the performance of the adaptive scheme in different channel conditions, where the acoustic channel either remained static or changed dynamically, with different MAC frame sizes. We use the energy efficiency resulted from the static BPSK scheme as the base line and show the improvement achieved by the adaptive scheme. The bottom line was obtained in a 1-hour period from 22:03

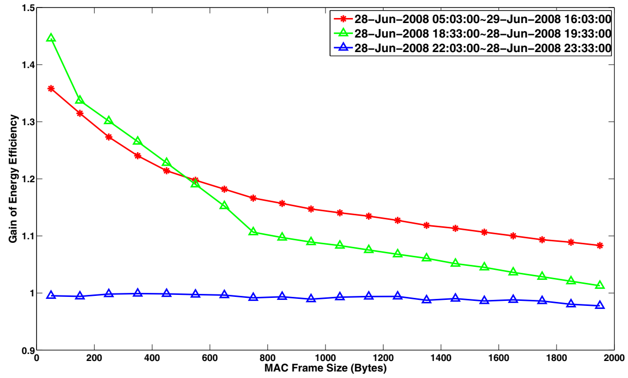


Fig. 10. Effects of channel fluctuation on the gain of energy efficiency (transmitter at 82.5 m below the sea surface).

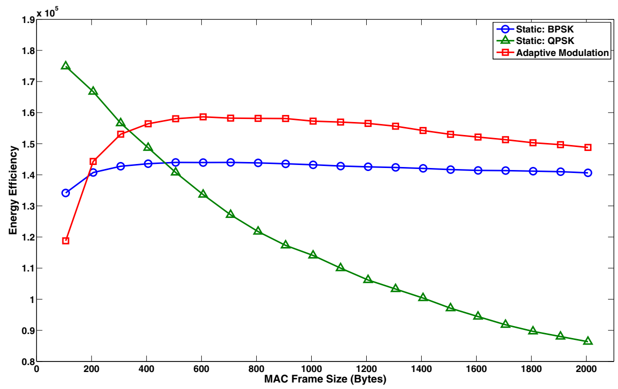


Fig. 11. Energy efficiency with probe message considered (transmitter at 82.5 m below sea surface).

to 23:33, June 28th when the channel remained relatively static and the output SNR is low. The adaptive scheme gives no improvement of energy efficiency over static BPSK. In contrast, from 18:33 to 19:33, June 28th, when the condition of the acoustic channel fluctuated drastically during that 1-hour period, the adaptive scheme outperformed static BPSK by 45% when the MAC frame size was small. The line with diamonds shows the improvement when the transmitter at 82.5 m below the sea surface sends messages for the entire 35-hour period.

C. Effects of probe messages

In the previous simulation scenarios, we assume transmitters can detect the instantaneous channel condition before sending data frames and choose proper scheme to modulate outgoing messages. Fig. 11 shows the effects of probe messages (as overhead) on energy efficiency. The energy efficiency becomes poor when MAC frame size is smaller. This is due to the fact that transmissions of probe and probe reply messages consume extra energy and the improvement of packet delivery rate cannot compensate for the energy consumption. However, when the MAC frame size is larger than 400 bytes, the adaptive scheme can still outperform static schemes and the largest improvement in energy efficiency against static modulation schemes can still be 10.1%.

VI. Conclusion

The paper described our efforts of programming physical measurements of realistic acoustic communications into a custom acoustic channel simulation model for a commercial network simulator. To demonstrate the utility of the custom acoustic channel model, we simulated a networking scenario that used an adaptive modulation scheme to optimize energy efficiency. The lesson learned could be applied to program other field measurements into network simulators to facilitate realistic simulation of underwater acoustic networks.

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