PHY-layer link quality indicators for wireless networks using matched-filters

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***Abstract*—We present a novel approach to accurate real-time estimation of wireless link quality using simple matched-filtering techniques. Our approach is based on the simple observation that there is a portion of each packet transmission from any given node that does not change from one packet to another; this includes preamble sequences used to synchronize the receiver and also address information in the packet header used for medium access control and routing. Our approach can be thought of as a generalized and simplified variant of standard signal processing techniques that are commonly used for preamble detection, automatic gain control, carrier sensing and other functions in many packet wireless networks. By using a combination of energy detection and correlation techniques, we show that we can effectively detect packet transmissions in real-time with low complexity, without decoding the packets themselves, and indeed, even without detailed knowledge of the packet format. We present extensive experimental results from a software-defined radio testbed to illustrate the effectiveness of this approach for 802.15.4 (Zigbee) networks even in the presence of strong interference signals and low SNR.**

I. Introduction

This paper is motivated by the problem of link quality estimation in wireless networks. Previous work has established that availability of link quality indicators (LQI) can substantially improve the performance of medium access control (MAC) and routing protocols in wireless networks. Consequently, there has been a lot of work on designing networking protocols that assume accurate and timely LQI estimates. Furthermore the accuracy and timeliness of the LQI information has a significant effect on network performance. However, existing LQI estimators are very crude, being constrained by very minimal hardware support and protocol layering considerations. We present in this paper a novel approach using matched-filtering techniques that can provide significantly richer LQI information with minimal overhead and processing complexity.

A. Motivation and problem statement

The main challenge in obtaining good estimates is the overhead cost in terms of power consumption and complexity. Wireless link states vary rapidly because of fading and mobility effects, so LQI estimates need to be frequently updated. Receiver hardware is usually powered off unless a packet is detected for decoding, so there is typically very limited hardware support for continuous link monitoring. Usually the hardware support takes the form of a quantized received signal strength information (RSSI) signal that is updated frequently and continuously (typically every few symbol intervals). While the RSSI signal can be used to flag activity or inactivity in the medium, it cannot distinguish between different transmitters or interferers, and as a result, the RSSI signal cannot by itself be used to track the states of multiple links.

It is possible to augment the RSSI signal with other information to obtain better LQI estimates. For instance, apriori knowledge of transmission schedules of different nodes and channel fading statistics can be combined with RSSI to track link states. Packet failure rates and large link latencies have also been proposed as proxies to indicate a weak link. However, such additional information is not always available and such techniques often depend on strong modeling assumptions (e.g. long channel coherence times).

It is also possible to combine RSSI information with knowledge from the packet decoder about successful packet receptions for LQI estimation. However, this only works for successfully decoded packets, and does not provide information about transmissions not intended for the specific receiver. While, in principle, it is possible to configure the packet decoder to listen promiscuously to all transmissions in the network, in practice this has two serious limitations: (a) this greatly increases power consumption, and (b) this does not provide any information about packets that fail to decode because of collisions, interference or fading. This is an especially serious limitation on networks operating in a shared part of the frequency spectrum e.g. the ISM band or a cognitive radio application, where the interfering signal may come from a transmission on another network using completely different protocols and packet formats. Finally, there is limited standards support for cross-layer information sharing to facilitate more sophisticated LQI estimation.

B. Summary of contributions

We propose a novel approach for accurate, real-time LQI estimation using matched-filters and present an extensive set of experimental results that demonstrate the effectiveness of our approach. The basic idea behind our approach is to exploit the fact that there is a significant amount of redundancy in transmissions in modern wireless networks: every packet sent between the same pair of nodes have a significant number of symbols that are identical across packets. Thus if we correlate the received signal with a known sequence of symbols using a matched-filter, a sharp peak in the filter output is a good indicator of the presence of the symbols. The size of the peak provides an estimate of the link channel strength.

Additionally, there are a number of symbols (e.g. source and destination addresses) that are always distinct for packets

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between different pairs of nodes. Thus we can use a bank of parallel filters each matched to a different set of symbols to identify specific transmitters.

Our main contributions are summarized as follows.

1) We describe an algorithm using peak detection on the output of matched-filtering complex baseband samples of the signal at a receiver to accurately detect, identify and classify packet transmissions.
2) We show that our matched filtering approach can effectively detect and identify packet transmissions even without any knowledge of the packet format, simply by using a noisy recorded copy of a previous transmission as a template for the matched-filter.
3) While continuously-running matched filters can be expensive in terms of computation and power consumption, we show that a simple energy detector with a threshold to trigger the filters on when an incoming transmission is detected, works well to minimize the overhead cost of the filters.

We implemented these ideas on a testbed using Zigbee transmitters and a software-defined radio receiver and verified their effectiveness for LQI estimation.

C. Background and related work

Network and link-layer protocols for wireless network protocols share a common lineage with those for wired networks; however it is well-known that wireless networks has peculiarly challenging features such as a large range of variation of signal power [1], fading and time-varying channels [2] and link asymmetries [3], hidden and exposed terminals [4] and so on. Link quality estimation has long been recognized as a classical problem for wireless networks [5] as a way of addressing these challenges. More recently the development of ad-hoc and sensor networks has led to a renewed surge of interest in this topic [6]. Several protocols have been designed that can take advantage of LQI information to realize significant improvements in network performance [7]–[9], and the IEEE 802.15.4 standard includes specifications for LQI [10].

However the problem of LQI estimation still remains very much open [11], [12]. One important reason for this is that protocol layering constraints have limited effective sharing of information relevant to LQI estimation from the PHY and link layers to higher level protocols [13]. There is also a tradeoff between the overhead cost of continuously monitoring transmissions on the medium and the accuracy of the measured LQI information. Partly because of these tradeoffs, many LQI estimation techniques [14] rely on packet success probabilities and similar measures that can be easily monitored by higher layer protocols. Hardware support for LQI is most commonly available in the form of a quantized received signal strength indicator (RSSI); RSSI signals are useful not just for LQI, but also for performing energy detection to assist in carrier-sensing [15] and other MAC functions. A comparative study of the performance of commonly used LQI estimation metrics is presented in [16].

1) Relationship to preamble-detection filters: All packet networks use a preamble sequence [17] at the beginning of packet transmissions to aid the receiver in detecting and "acquiring" the incoming signal [18], a process that typically involves determining the frame boundary, symbol boundaries and carrier frequency and phase offsets. The preamble sequences are carefully designed to have a sharply peaked auto-correlation function, and matched-filters are universally used to detect the preambles and estimate their precise timing. The preamble-detection filters are also sometimes used for coherent carrier-sensing [15] for medium access control.

Our approach is also based on this same idea of detecting correlation peaks; so a natural question is: can we leverage the preamble-detection filter to also perform LQI estimation perhaps with some minor modification? This is an attractive possibility because it could potentially give us LQI estimation free-of-cost simply as a by-product of the signal acquisition process.

However, the LQI estimation process differs in some fundamental respects from preamble-detection. Specifically, the preamble detection function is expected to produce a very fine-grained estimate of the timing of the correlation peak, because the carrier and symbol timing synchronization algorithms depend sensitively on this estimate. Also preamble detection errors can be extremely costly in terms of performance, e.g. false alarms trigger spurious collision detects which can degrade the medium-access control function while missed detection events lead to packet losses.

Thus, preamble detection filters are typically implemented with very high precision computations e.g. with 16-bit quantized samples. This can be extremely power-hungry, and indeed there has been some interesting recent work [19] on dynamically switching between high and low precision calculations to minimize the power consumption.

Since LQI estimation is far more tolerant of estimation errors, it is not obvious what is the optimal way to jointly implement this function with other PHY tasks. For the purposes of this paper, we assume that the different matched filters used at the receiver are all independent and running in parallel and we defer the details of their optimal implementation for future work.

D. Outline

The rest of the paper is organized as follows. In Section II we describe our proposed technique for link estimation. We present a detailed set of experimental results demonstrating the performance of our approach in Section III. Specifically, we consider the "protocol-aware" case in Section III-A (where the receiver knows the packet format and has a noiseless copy of a known sequence of samples for each link being monitored), and Section III-B addresses the "protocol-blind" case (where the links being monitored use packet formats unknown to the receiver). Section IV concludes.

II. Proposed technique for signal detection using matched-filters

We describe our proposed technique for signal detection using matched filters. The goal of the detection procedure is simply to tell if a packet was transmitted and if so from which

transmitter. The receiver node, Rx0, which does the detection is depicted in Fig. 1 below. In our setup, Rx0 is an ettus USRP N200 with a RFX2400 daughter board.

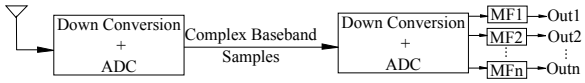

Fig. 1. Signal detection scheme

The MF block as shown in Fig. 1 is the block that performs all the relevant discrimination of received samples. There are three major steps in this block which are controlled by three threshold applications. The first step is to detect whether the received signal is above the noise floor. An energy detection threshold T1 is applied. If the energy of the received signal is above T1, then the matched filter value is computed else it is set to zero. This ensures that energy is conserved until there is a potential packet arriving. The matched filter output denoted mf, given N filter taps h and received signal samples, x is found by

$$mf[i] = \sum_{k=i-N+1}^{i} h[i-k]^* x[k] \tag{1}$$

The second step is to detect whether there is a relevant match between the received signal and the filter taps after T1 has been satisfied. This is checked using a simple metric, denoted m, given by

$$m[i] = \frac{mf[i]}{mf[i-1]} > T2 \tag{2}$$

It should be noted that when there is a packet, the value of the matched filter output is bell shaped. Hence there has to be a metric value greater than 1 if there is a packet matching the taps present in the captured samples. To reduce the number of computations, values of the matched filter threshold T2 greater than 1 can be utilised.

The third step is to evaluate the correlation coefficient given that thresholds T1 and T2 have been satisfied. We use the Pearson correlation coefficient, denoted c, thus

$$c[i] = \frac{mf[i] - \frac{\sum_{k=1}^{N} h[k] \sum_{k=z}^{i} x[k]}{N}}{\sqrt{(\sum_{k=z}^{i} x^2[k] - \frac{(\sum_{k=z}^{i} x[k])^2}{N})(\sum_{k=1}^{N} h^2[k] - \frac{(\sum_{k=1}^{N} h[k])^2}{N})}} \tag{3}$$

$$z = i - N + 1 \tag{4}$$

The third threshold T3 is finally applied to the output of c. If the output meets the threshold it is kept, else the value is set to zero. The norm of c is between 0-1 and a value close to 1 denotes a match. Satisifying all three thresholds implies there was a packet related to a particular match filter and its filter taps.

The pseudo-code for this algorithm described above is given in algorithm 1.

Algorithm 1 Signal detection algorithm at each MF block

```
Initialization:
T1 ← received_signal_strength_threshold
T2 ← matched_filter_metric_threshold
T3 ← correlation_coefficient_threshold
while receiver_Rx0_is_running do
  if received_signal_strength > T1 then
    Compute matched_filter_output
    Compute matched_filter_metric_output
    if matched_filter_metric_output > T2 then
      Compute correlation_coefficient_output
      if correlation_coefficient_output <= T3 then
        correlation_coefficient_output ← 0
      end if
    else
      correlation_coefficient_output ← 0
    end if
  else
    matched_filter_output ← 0
    correlation_coefficient_output ← 0
  end if
end while
```

III. Experimental results

We now present experimental results from our implementation. Fig. 2 shows a diagram of our experimental setup which comprises two transmitter nodes, Tx1 and Tx2 with corresponding receivers Rx1 and Rx2, an interfering signal transmitter, If1, and an eavedropper Rx0 within range of both Tx1 and Tx2 which is going to be used to detect the presence or absence of packets transmitted by Tx1 and Tx2. The hardware equipment used for the two types of experiments, thus protocol-aware signal detection and protocol-blind signal detection are described in the sections below with the observed results.

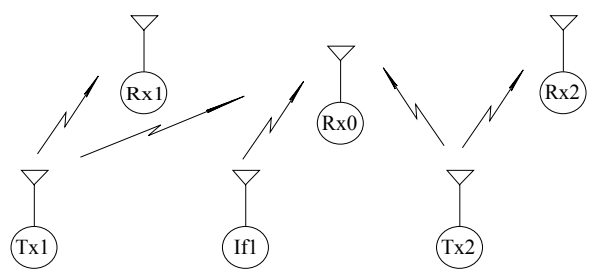

Fig. 2. Experiment setup for signal detection.

A. Protocol-aware signal detection

In the protocol-aware signal detection setup, Tx1, Tx2, If1, Rx0, Rx1 and Rx2 are all USRP N200 nodes with RFX2400 daughter boards. The pre-recorded packet samples used for the two filter taps corresponding to Tx1 and Tx2 are 128

samples generated from the one byte start frame delimiter (SFD). Two different SFD values of 0xA7 and 0x98 are used to distinguish between the two packets. The UCLA zigbee PHY package is used for generating the zigbee packets [20] [21]. The USRP N200 node If1 transmits pre-recorded gmsk packets as an interfering signal. All signals are transmitted at a Radio frequency(RF) of 2.48GHz. The parameters used for the experiment at Rx0 are energy detection threshold T1=0.01, matched filter metric threshold T2=1 and correlation coefficient threshold T3=0.8 for both filters. Tx1, Tx2 and If1 all transmit one packet every half second. Results of the received signal strength(RSS), matched filter output and correlation coefficient output are shown in Figs. 3-5.

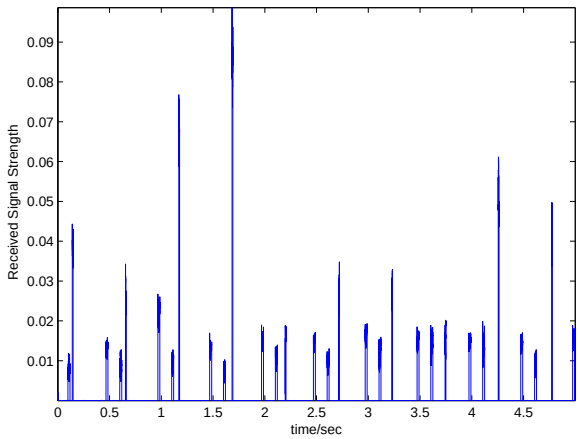

Fig. 3. Received RSS at Rx0 using USRP N200 transmitters

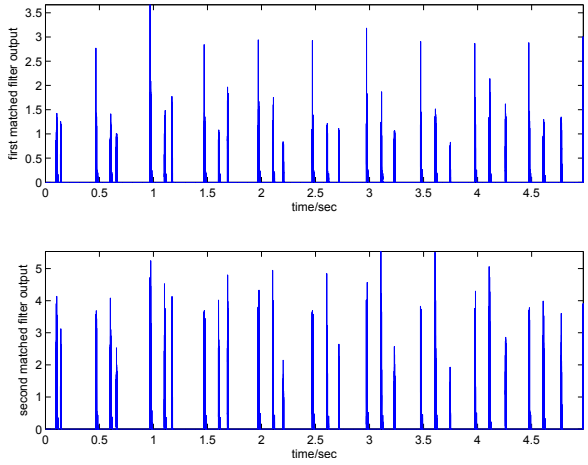

Fig. 4. Matched filter output at Rx0 using USRP N200 transmitters

From Figs. 3-5, it is clear that the RSS plot shows all three signals, thus the two desired packets as well as the interfering signal, whiles the matched filter plot also looks similar to RSS plot albeit at different scales. The correlation coefficient plot however separates the two desired packets. The correlation coefficient plot corresponding to the packets from Tx1 completely eliminates the packets from Tx2 and If1. A similar observation holds for the correlation coefficient plot corresponding to packets from Tx2.

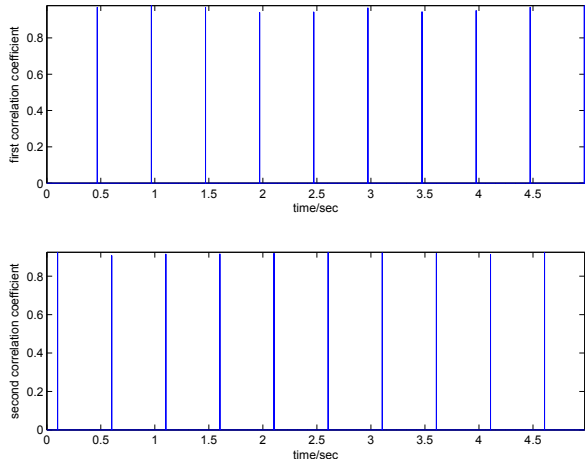

Fig. 5. Correlation coefficient output at Rx0 using USRP N200 transmitters

B. Protocol-blind signal detection

In the protocol-blind signal detection setup, Tx1, Tx2, Rx1 and Rx2 are crossbow telosb motes whiles If1 and Rx0 are USRP N200 nodes. The pre-recorded packets samples used for the two filter taps corresponding to Tx1 and Tx2 packets are 576 samples generated from four bytes in the address information. Specifically the AM broadcast address information is used. The samples however are noisy and are recorded at the Rx0 at a sampling rate of 4MHz. Two different AM broadcast address information of 0xAAAA and 0x37BD are used for the two motes to distinguish between the two packets. Tinyos 2.0.2 is used for generating the packets and compiling the binary image unto the telosb motes. The USRP N200 node If1 again transmits pre-recorded gmsk packets as an interfering signal. The parameters used for the experiment at Rx0 are energy detection threshold T1=0.01, matched filter metric threshold T2=1 and correlation coefficient threshold T3=0.8 for both filters. Tx1 and Tx2 transmit one packet every second whiles If1 transmits a packet every half second. Results of the RSS, matched filter output and correlation coefficient output are shown in Figs. 6-8.

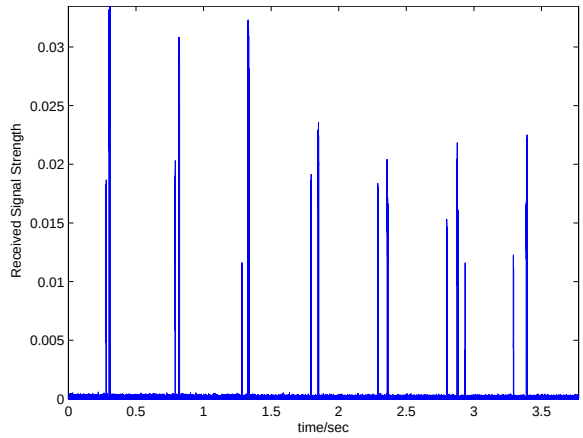

Fig. 6. Received RSS at Rx0 using telosb motes as transmitters

From Figs. 6-8, it is clear that the RSS plot shows the two

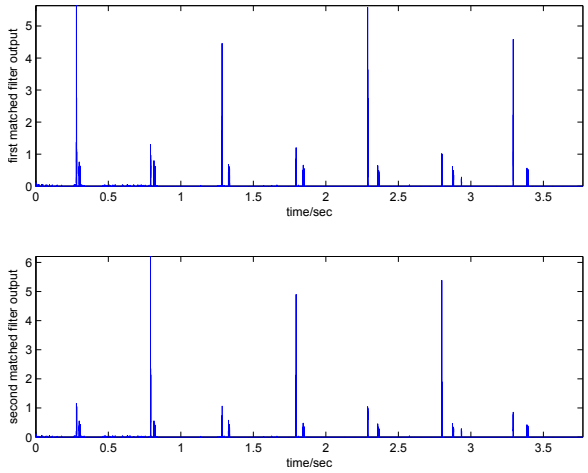

Fig. 7. Matched filter output at Rx0 using telosb motes as transmitters

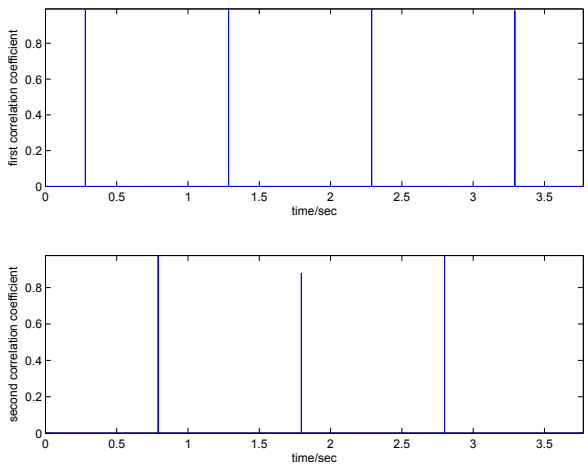

Fig. 8. Correlation coefficient output at Rx0 using telosb motes as transmitters

desired packets as well as the interfering signal, whiles the matched filter plot also looks similar to RSS plot but has greater values for the desired packets. The correlation coefficient plot however clearly separates the two desired packets even though the filter taps are noisy. The correlation coefficient plot corresponding to the packets from Tx1 completely eliminates the packets from Tx2 and If1. A similar observation holds for the correlation coefficient plot corresponding to packets from Tx2.

Another experiment was conducted to clearly show that even in the case where the interfering signal coincides with desired packets, we are still able to detect the packets. In this experiment, the parameters for Tx1 and Tx2 are maintained as above but If1 now transmits a constant continuous burst at the same RF frequency of the two telosb motes. The parameters used for the experiment at Rx0 are energy detection threshold T1=0.01, matched filter metric threshold T2=1 and correlation coefficient threshold T3=0.5 for both filters. It is worthy of note that reducing the signal-to-noise-plus-interference (SNIR) only affects the maximum value of the peak correlation coefficient and therefore necessitates reducing the correlation coefficient threshold appropriately. Results of the received signal strenghth(RSS), matched filter output and correlation coefficient output are shown in Figs. 9-11.

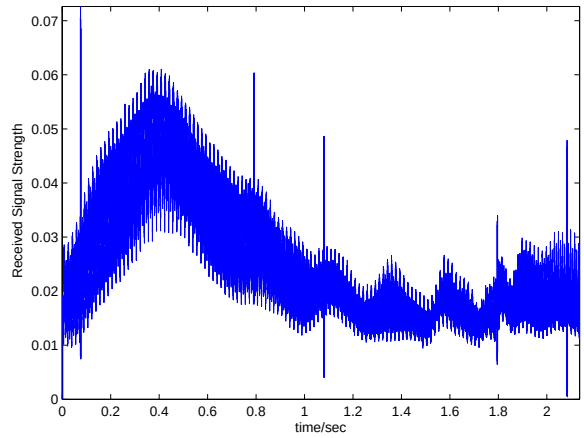

Fig. 9. Received RSS at Rx0 using telosb motes as transmitters

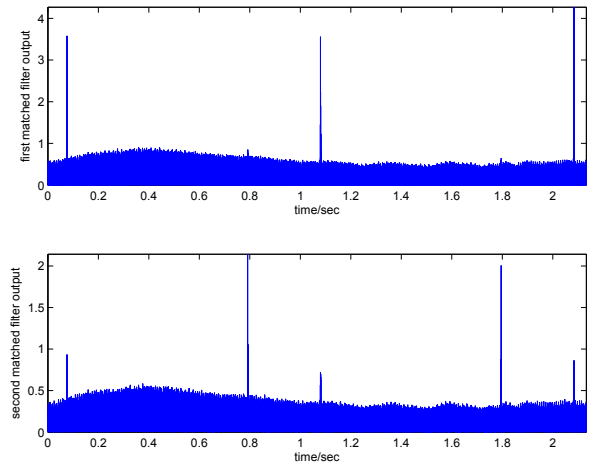

Fig. 10. Matched filter output at Rx0 using telosb motes as transmitters

From Figs. 9-11, it is seen that the two packets are again easily distinguishable even at SNIR below 0dB since the transmit power of the telosb motes were kept at the same level as the previous experiment. Reducing the SNIR only reduces the maximum peak of the correlation coefficient value. The correlation coefficient threshold will therefore have to be sized appropriately.

IV. Conclusion

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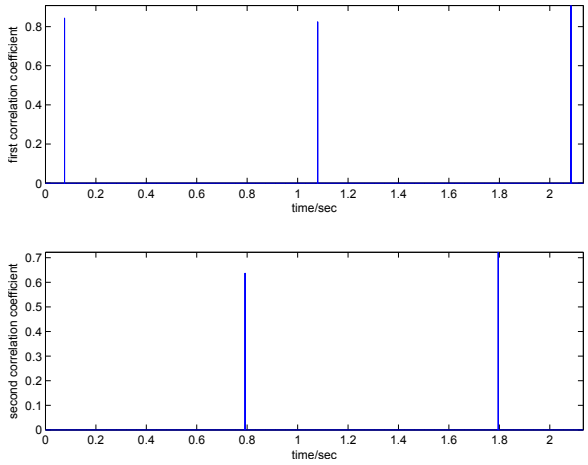

Fig. 11. Correlation coefficient output at Rx0 using telosb motes as transmitters

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