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TARGET DETECTION IN AN UNDERWATER ACOUSTIC NETWORK: LAKE EXPERIMENT

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Abstract: *The aim of this work is to investigate the target detection performance of a distributed underwater acoustic (UWA) communication network with lake experimental data. In recent work, a target detection algorithm was proposed based on measurement of the time-varying channel impulse response (CIR) between a communication transmitter and receiver. The detector computes the normalized mean squared deviation (MSD) between a CIR of interest and a set of reference CIRs (estimated when the target is absent) and uses the minimum normalized MSD (nMSD) as the statistic for target detection. Before computing the nMSD, a filter is applied to the CIR to compensate for the change in delay and amplitude caused by environmental factors, such as node drift or moving surface waves. The performance of the detector was investigated in a small-scale lake experiment and showed clear indication of the target crossing the communication link. In this work, we improve the detector performance in fast-varying channels by updating the reference CIRs in time. The detection threshold is also time-varying and is computed using the current set of reference CIRs and a predefined false alarm rate. Instead of using the minimum nMSD, we exploit information from all nMSDs and make the detection decision by computing the probability of potential target crossing (percentage of nMSDs higher than the detection threshold). The performance of the new detector is investigated in an UWA network with nine communication links. Results show clear indication of target detection and a significant reduction of false alarms, compared to the previous work.*

Keywords: *Channel Estimation, Target Detection, Underwater Acoustic Network*

1. INTRODUCTION

Underwater target detection is a key part of an underwater monitoring and surveillance system. It is known that the forward scattering from a target generally has a higher intensity level compared to the back scattering [1]. Prior works perform target detection by building up an acoustic barrier with vertical source and receiver arrays covering the water column [1–3]. In this work, we consider target detection within an underwater acoustic (UWA) network of acoustic sensor nodes communicating with each other. The key idea is to detect the forward scattering from the moving target by re-using the communication signals in the network. For every data packet, measurement of the channel impulse response (CIR) is available at the receiver. The detector can exploit this information and perform target detection based on changes in the CIRs between the data packets. Potential target detection information will be delivered to a master station on shore for joint processing and/or target trajectory estimation. Network protocol design for simultaneous UWA communication and target detection can be found in [4].

In [5], we proposed a detection algorithm based on the variation of the CIRs. The normalized mean squared deviation (nMSD) between a reference CIR (measured when the target is absent) and the CIR of interest (measured with the current data packet) is used as the statistic for target detection. Before computing the nMSD, a filter with a small delay spread is applied to one of the CIRs to compensate for the change in delay and amplitude caused by the slow motion of the nodes and environmental factors. To further reduce the impact of channel variation on the detection performance in lake experiments, a set of reference CIRs measured outside of the experimental interval are used for computing the nMSDs. These reference CIRs should cover the uncertainty area caused by the channel variation due to the changing environment. Only the minimum nMSD among these measurements is used as the statistic for target detection. Both the channel variation and a moving target can cause high nMSD. Using the minimum nMSD allows us to reduce the influence of the channel variation on the nMSD performance.

In [5], a fixed set of reference CIRs are chosen at the beginning and the end of the lake experiment. This works for experiments of short duration under relatively stable channel conditions. For long-term surveillence and monitoring, it is not practical to use a fixed set of reference CIRs as it requires a very large dataset to cover the uncertainty in channel variation due to the time-varying environment over the whole deployment period. In this work, we propose to update the reference CIRs in time so that the detection system can track the changes of the channel state with a small set of reference CIRs. In addition, we set detection threshold based on a pre-defined false alarm rate using the reference CIRs. In such a case, for every new received data packet, we will have a new set of reference CIRs and a time-varying detection threshold for target detection. Furthermore, instead of using a single (minimum) nMSD for target detection, we propose to exploit all nMSDs in the reference set to compute the probability of a target crossing event.

The performance of the new detector is investigated and compared with the detector proposed in [5] in a lake experiment with three in-house developed transmitter nodes and four hydrophones. Results indicate a good detection performance against the ground truth with the proposed detector and a significant reduction of false alarms compared to the previous work.

2. Target detection based on CIR variation

2.1. Computation of the normalized MSD

The MSD can be computed using the frequency-domain representation of the channel:

$$\mathrm{MSD} = \sum_{k=0}^{K-1} |H_0(k) - H(k)|^2, \tag{1}$$

where H_0, H are the frequency responses corresponding to the reference CIR h_0 and the CIR of interest h, respectively, and they are computed using the fast Fourier Transform (FFT) of a size K.

Instead of computing the MSD using (1), we introduce an adaptive filter g with a small delay spread to compensate for the change in delay and amplitude caused by the slow motion of the nodes and the variations of the environment [5]. The frequency response of g can be expressed as a combination of complex exponentials with expansion coefficients $c(p)$ [6]:

$$G(k) = \sum_{p=0}^{2P} c(p) e^{j2\pi(-P+p)k/K}, \; k = 0, \ldots, K-1, \tag{2}$$

where the number of complex exponentials $2P + 1$ corresponds to the delay spread of the filter g. The filter g is found by solving the following optimization problem:

$$\hat{G} = \underset{G}{\operatorname{argmin}} \sum_{k=0}^{K-1} |H_0(k)G(k) - H(k)|^2. \tag{3}$$

Detailed procedure of finding $\hat{G}$ is described in [5]. After obtaining $\hat{G}$, the deviation in the frequency response is computed as: $\Delta H(k) = H_0(k)\hat{G}(k) - H(k)$. Finally, the nMSD is computed as:

$$\text{MSD}_{\text{norm}} = \frac{\|\Delta H(k)\|_2^2}{\|H_0(k)\|_2 \|H(k)\|_2}, \tag{4}$$

where $\|\cdot\|_2$ denotes the Euclidean norm.

2.2. Computation of the Detection threshold

To compute the detection threshold, the nMSD between each pair of reference CIRs in the dataset needs to be computed. Assuming that the number of reference CIRs is N, we will have $N(N-1)$ measurements of the nMSD.

The detection threshold Γ is initialized to a very small value (starting with a high false alarm rate) and iteratively increased until the false alarm rate is equal to or lower than a pre-defined value a. In every iteration, we compare the nMSDs with Γ and count the number of times (N_{fa}) when the nMSD is higher than Γ. The false alarm rate P_{fa} is computed as: $P_{\text{fa}} = N_{\text{fa}}/(N(N-1))$. If the false alarm rate is higher than a, the threshold is exponentially increased as: $\Gamma = (1+\alpha)\Gamma$, where α represents the growth rate. The above procedure is repeated recursively until the pre-defined false alarm rate is met.

The algorithm for the threshold computation is summarized in Algorithm 1, where $\text{MSD}_{\text{norm}}(i, j)$ is the nMSD between the ith and the jth reference CIR.

2.3. Target detection

The performance of channel estimation is a key for target detection. To ensure high accuracy of the channel estimates, we only use the CIRs from perfectly demodulated data packets. These CIRs are further selected based on the signal to noise ratio (SNR) in the received data packet; if SNR is lower than a threshold, the CIR is discarded.

The reference CIRs are initialized with N CIRs measured assuming there are no targets in the vicinity of the communication link. The set of reference CIRs are updated as follows. For the nth data packet, we include a CIR measured at the $(n-l)$th data packet into the reference CIRs and remove the oldest reference CIR. As the target can be detected when it is in close proximity to the communication link, introducing a delay of l data packets allows us to ensure the reference CIR is not affected by the target. After updating the set of reference CIRs, a

Algorithm 1 Detection threshold computation

Initialization: $\Gamma = \Gamma_{\text{init}}$, $N_{\text{fa}} = 0$, $P_{\text{fa}} = 1$
while $P_{\text{fa}} > a$ **do**
  $\Gamma = (1 + \alpha)\Gamma$ and $N_{\text{fa}} = 0$
  Update MSD_{norm}
  for $i = 1, \ldots, N$ **do**
    for $j = 1, \ldots, N$ **do**
      if $\text{MSD}_{\text{norm}}(i, j) > \Gamma$ **then**
        $N_{\text{fa}} = N_{\text{fa}} + 1$
      end if
    end for
  end for
  $P_{\text{fa}} = N_{\text{fa}}/(N(N-1))$
end while

detection threshold is computed based on Algorithm 1. As only one of the reference CIRs is updated, only one row and one column of the matrix MSD_{norm} need to be re-computed for every data packet.

Then, we compute the nMSDs between the current CIR and the reference CIRs and compare them with the detection threshold Γ. The propability of the target crossing can be computed as: $P_{\text{d}} = N_{\text{d}}/N$, where N_{d} is the number of times when the nMSD is higher than Γ. The detector will only indicate a target being detected when $P_{\text{d}} > 0.5$. The algorithm for target detection is summarized in Algorithm 2, where h_0^i represents the ith reference CIR and h represents the CIR measured with the current data packet.

Algorithm 2 Target detection algorithm

while A data packet being received **do**
  Initialization: $N_{\text{d}} = 0$
  Replace h_0^0 in the reference CIRs with h_{n-l}
  Compute the detection threshold Γ using Algorithm 1
  for $i = 1, \ldots, N$ **do**
    Compute $\text{MSD}_{\text{norm}}(i)$ between h_0^i and h according to subsection 2.1
    if $\text{MSD}_{\text{norm}}(i) > \Gamma$ **then**
      $N_{\text{d}} = N_{\text{d}} + 1$
    end if
  end for
  $P_{\text{d}} = N_{\text{d}}/N$
  if $P_{\text{d}} > 0.5$ **then**
    Target detected!
  end if
end while

3. LAKE EXPERIMENT

3.1. EXPERIMENT TOPOLOGY

Fig. 1 shows the topology of the lake experiment and the target trajectory and measurements of the sound velocity. In total, three transmitter nodes (Tx1 to Tx3) and four hydrophones (H1 to H4) are deployed. The signal from H3 is not used due to the recorder artifacts, thus we have nine communication links in the experiment. Depth of the nodes and distance of the acoustic links

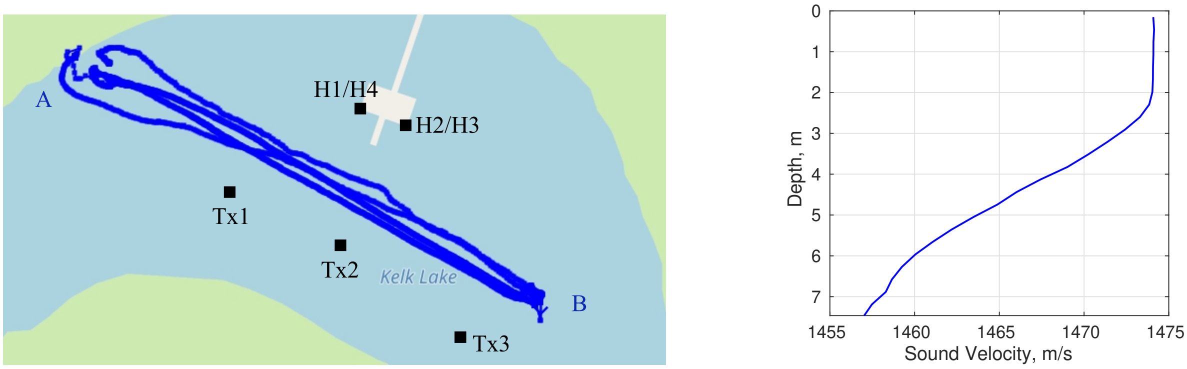


Figure 1: Topology of nodes and target trajectory (blue dots) in the lake experiment (left) and sound velocity measurements (right).

Table 1: Nodes depth and distance between nodes.

	H1/H4	H2	Tx1	Tx2	Tx3	Depth
Tx1	49 m	61 m		39 m	91 m	2.5 m
Tx2	46 m	46 m	39 m		53 m	2.5 m
Tx3	88 m	78 m	91 m	53 m		3.9 m
H1		17 m	49 m	46 m	88 m	1.8 m
H2	17 m		61 m	46 m	78 m	1.6 m
H4			61 m	46 m	78 m	5.8 m

are summarized in Table 1. The target used in this experiment is a 1 m $\times$ 0.9 m wooden board with gravels on both sides. The board is deployed at approximately 1.5 m depth. A buoy with a GPS recorder is attached to the board to record the target trajectory. During the experiment, the board crossed the network area four times between point A and point B. Initially, the board is towed by a canoe with a 7 m long rope when travelling from point A to point B. The board is then released from the canoe and pulled back to point A with a fishing line. This process was repeated twice within the experiment.

3.2. Data packet transmission

During the experiment, we have three unsynchronized transmitter nodes transmitting data packets at 32 kHz carrier frequency with 6 kHz frequency bandwidth. The duration of each data packet is 100 ms. The transmitter source level is 155 dB re 1μPa @1m. Each user transmits three data packets every ten seconds. As shown in Fig. 2, the gap between data packet transmission is 0.4 s, 1.2 s and 2.8 s for Tx1, Tx2 and Tx3, respectively. In each data packet, 200 bits of uncoded data are transmitted, where the last 16 bits are cyclic redundancy check (CRC) code.

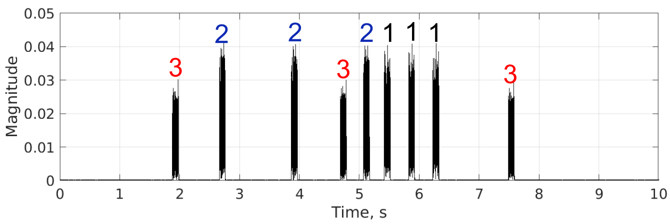


Figure 2: Ten seconds of baseband received data packets from Tx1, Tx2 and Tx3 (denoted as 1, 2 and 3, respectively).

To address the possible overlap in the received data packets from the unsynchronized transmitter nodes, a multiuser UWA receiver with interference cancellation [7] is used to demodulate the data packets from three users and to provide channel estimates for target detection. After a data packet detection, the received signal segment is downsampled to twice the baseband sampling rate and de-multiplexed into two branches for channel estimation and equalization. The final CIR used for target detection is obtained by combining (multiplexing) the channel estimates from the two branches (with 1/(12 kHz) $\approx$ 0.08 ms delay resolution).

3.3. Target detection performance

In this section, we investigate and compare the target detection performance of the new detector and the previous design in [5].

A fixed set of reference CIRs is used for target detection in [5]. For each acoustic link, 200 reference CIRs are measured when the target is far away from the link are used. Method for threshold computation was not proposed in [5]. Here we compute the threshold in a similar way as described in Algorithm 1. For every reference CIR, we compute the nMSDs with the rest of the reference CIRs, excluding two adjacent CIRs, which are supposed to be highly correlated with the current CIR, and use the minimum nMSD for target detection. The $(N-1) \times N$ nMSD matrix in Algorithm 1 is reduced to an $(N-3) \times 1$ column vector (removing the current reference CIR and two neighbouring ones). The acceptable false alarm rate is set as $a = 0.5\%$.

In Fig. 3, data packets with nMSD higher than the detection threshold are shown in blue stems. These potential crossings are validated with the ground truth of the target trajectory. If the target position is within 10 m distance from the crossing point indicated by the GPS, it is considered as a positive detection. If not, it is marked as false alarm by a black cross. All positive detections are denoted with a number indicating the associated crossing event (from 1 to 4).

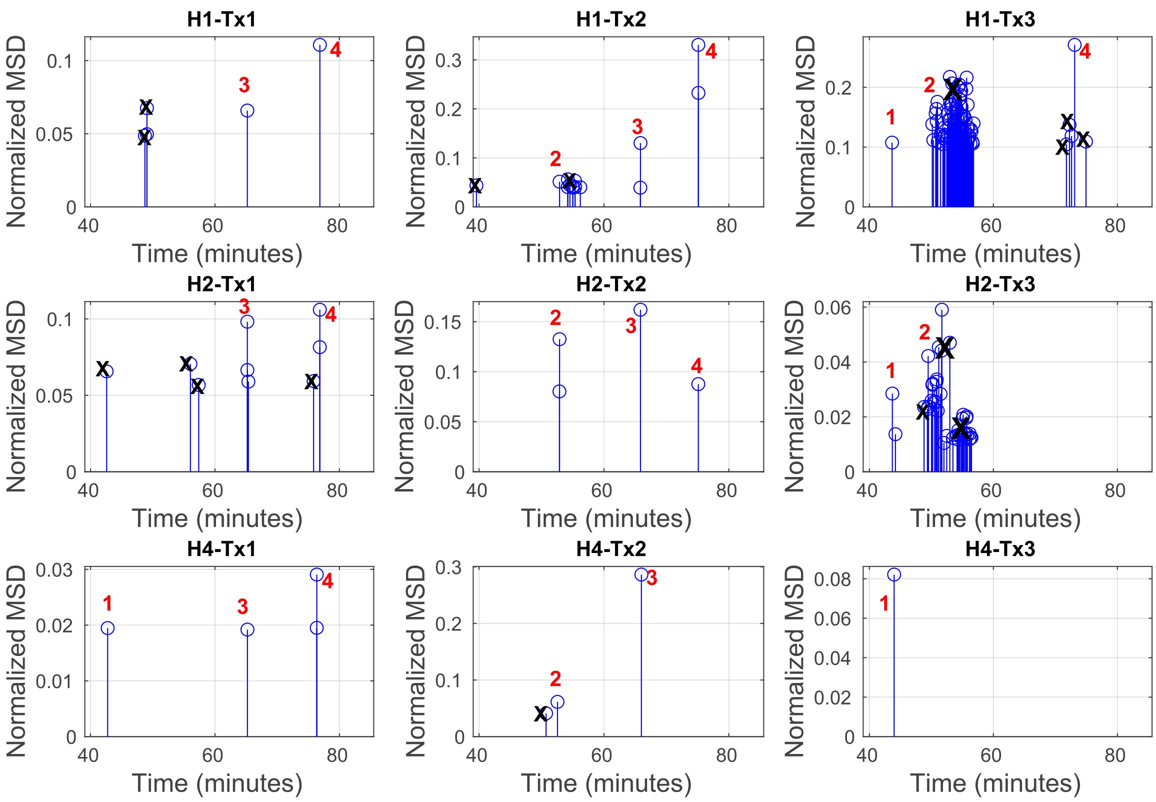
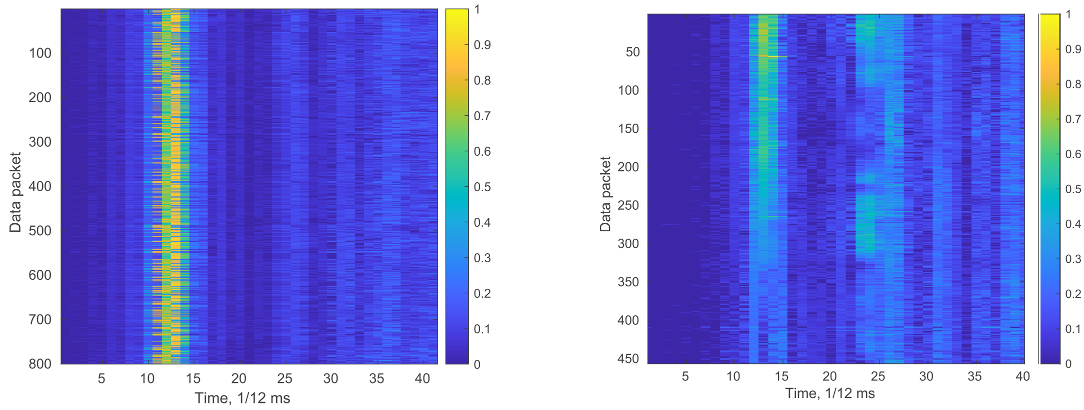


Figure 3: Normalised MSD of potential target crossings indicated by the detector in [5].

It can be seen from Fig. 3 that the detector can provide reasonable target detection performance for most of the acoustic links; at least four positive detections are reported in the network for



(a) CIRs between H1 and Tx1 .

(b) CIRs between H1 and Tx3.

Figure 4: Channel impulse responses of perfectly demodulated data packets between (a) H1 and Tx1 and (b) H1 and Tx3.

each target movement between A and B (see Fig. 1). However, there are many false alarms among these detection, especially for links H1-Tx3 and H2-Tx3. In Fig. 4, we show the CIRs obtained for the link between H1 and Tx1 and the link between H1 and Tx3, respectively. It can be seen that the multipath structure in Fig. 4(a) is relatively static, on the other hand, significant change in the CIRs can be observed in Fig. 4(b). This explains the sudden change in the nMSD shown in Fig. 3, which results in a large number of false alarms with a fixed detection threshold.

The sudden change in the channel state can be resolved by the new detector as both the reference CIRs and the associated detection threshold are changing in time. The number of reference CIRs used in the new detector is 50. For every data packet, the oldest reference CIR is replaced by a CIR measurement delayed by three data packets (corresponds to at least 10 second based on the transmission pattern) to ensure the reference CIR is measured when the target is not crossing the communication link.

Potential target crossing events in all acoustic links are shown with blue stems in Fig. 5, among which false alarms are marked by black cross symbols. Multiple positive detections are reported in the UWA network for each target movement between A and B. In addition, the number of false alarms is significantly reduced for the link between H1 and Tx3 and the link between H2 and Tx3. This demonstrates the effectiveness of the new detection algorithm.

4. Conclusions and future work

In this work, a new detector is proposed for target detection in an UWA communication network. The target detection is performed based on computing the nMSD between a CIR and a set of reference CIRs. To improve the detector performance in fast-varying channels, both the reference CIRs and the detection threshold are updated in time. The probability of a target crossing is then computed as the percentage of nMSDs higher than the detection threshold. If the probability is higher than 50%, the detector decides that there is a target crossing. The performance of the proposed detector is investigated and compared with our previous detector in a lake experiment with nine acoustic communication links. Results indicate a high detection performance has been achieved with less false alarms compared to the previous design.

The performance of the proposed detector will be further validated with sea experimental data. The next step of the research is to propose an algorithm for target trajectory estimation and prediction based on the detection information from all acoustic links in the UWA network.

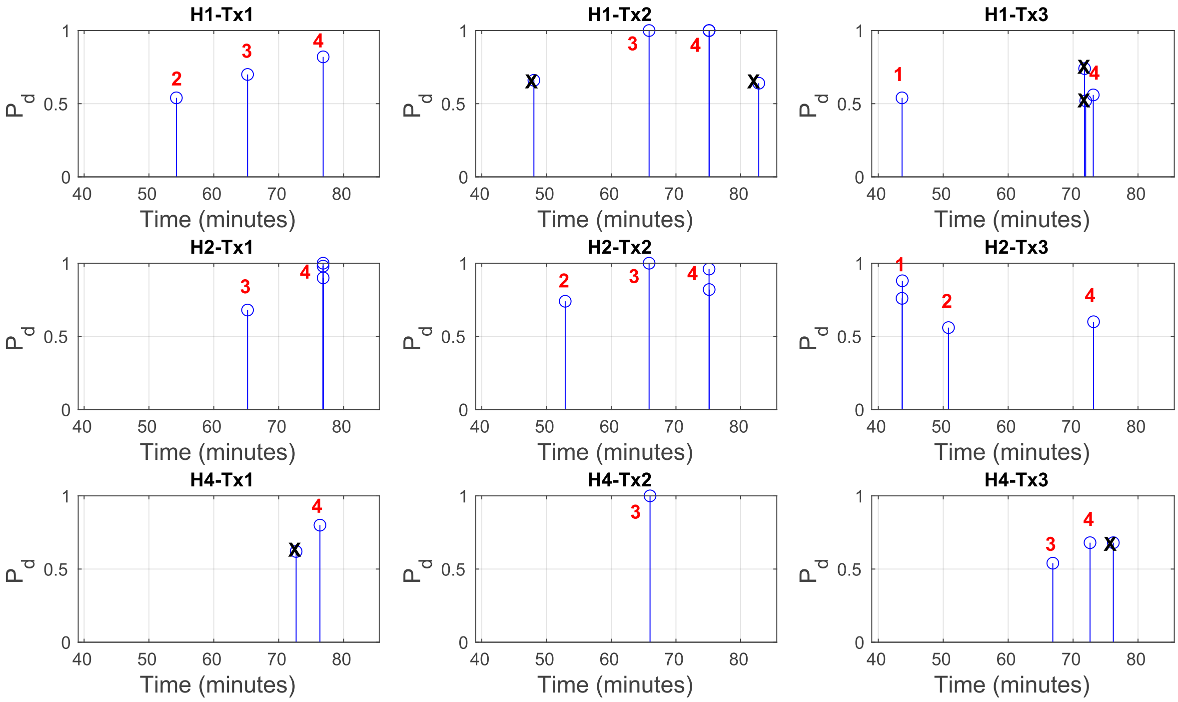


Figure 5: Probability of potential target crossing computed by the proposed detector.

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