

Research Article

Detecting Network Intrusions Using Signal Processing with Query-Based Sampling Filter

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This paper presents a novel approach for training a network intrusion detection system based on a query-based sampling (QBS) filter. The proposed QBS filter applies the concepts of data quantization to signal processing in order to develop a novel classification system. Through interaction with a partially trained classifier, the QBS filter can use an oracle to produce high-quality training data. We tested the method with a benchmark intrusion dataset to verify its performance and effectiveness. Results show that selecting qualified training data will have an impact not only on the performance but also on overall execution (to reduce distortion). This method can significantly increase the accuracy of the detection rate for suspicious activity and can recognize rare attacks. Additionally, the method can improve the efficiency of real-time intrusion detection models.

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1. Introduction

The Internet has become an important resource for information access and a battlefield for business competition. A critical issue arising from the rapid advance of the Internet is information and communication security. Users, particularly high volume users, are exposed to a wide range of security threats through software or design vulnerabilities. Network attacks can cause serious performance problems throughout the network. These include common network attacks such as denial of service (DoS), which either jam a network pathway or exhaust available computer resources, thus disrupting related network services.

In order to respond to this increasing threat, information security technology provides a range of tools known as intrusion detection systems (IDSs), and in its latest development, IDS attempts to stop these attacks by scanning network traffic for signatures, for policy anomalies, such as variations in traffic or network protocol that can signal impending illegal activity, and also for signs of unwarranted activity that could point to attacks from inside or outside the network. Figure 1 illustrates the intrusion detection system and external/internal network intrusion attacks.

The main goal of an intrusion detection system is to accurately detect anomalous network behavior or misuse of

resources, to differentiate true attacks from false alarms, and subsequently to notify network administrators of the activity. The intrusion detector learning task is to build a predictive model (i.e., a classifier) capable of distinguishing between malicious intrusions and normal connections. In typical applications of machine learning algorithms (e.g., artificial neural networks) to intrusion detection, detection models are produced offline because the learning of algorithms involves processing tremendous amounts of archived audit data. These models can naturally be applied to offline intrusion detection (to analyze audit data offline after intrusions have run their course). Effective intrusion detection should happen in real time, as intrusions take place, to minimize compromises of security. Therefore, their success usually depends on the quality of the training data. If the data contain extraneous and irrelevant information, machine-learning algorithms may produce less accurate and less understandable results. To address this shortcoming, we classify extraneous and irrelevant data as noisy data and utilize the concepts of signal processing techniques to filter them out.

In our previous research [1, 2], we applied the query-based learning concept to backpropagation neural networks in a training procedure. It designed an oracle in the learning loop. The oracle can actively and repeatedly add training

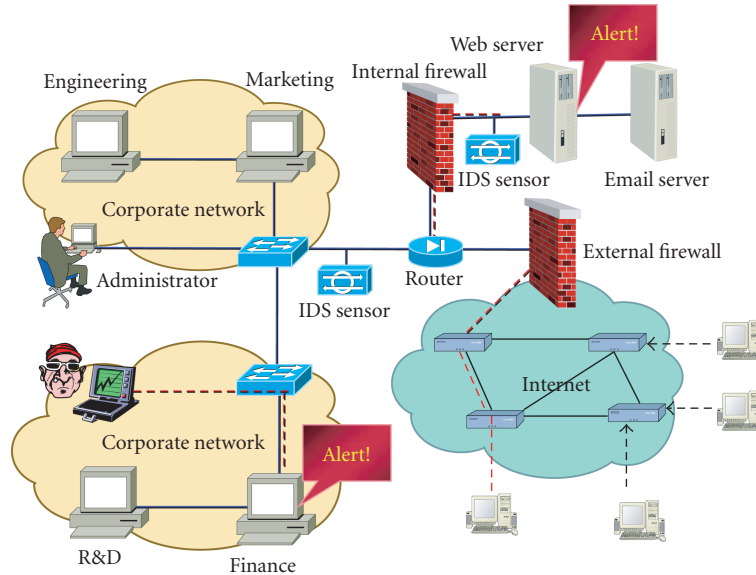


FIGURE 1: The intrusion detection system and external/internal network intrusion attacks.

samples for better training. In this study, we explore the concepts of data quantization for signal processing to develop a novel classification system. Through interaction with a partially trained classifier, the QBS filter can use an oracle to produce high quality training data and then construct backpropagation neural networks to predict attacks. By using QBS for attack detection, the prediction model develops the generalization capability from training data. The approach is evaluated against the KDD Cup 1999 intrusion detection evaluation data [3].

In addition to the introduction, there are four other sections to this paper. Section 2 reviews related literature and establishes the foundation of current knowledge. Topics related to intrusion detection and neural networks are introduced. Section 3 introduces a query-based method that combines neural networks into one composite back-propagation neural network. Section 4 discusses how to increase the accuracy detection rate and how to improve the efficiency of the intrusion detection models. We compare the prediction performance of the developed QBS and conventional stratified sampling. Section 5 summarizes all findings in this study with suggestions for future study.

2. Related Works

An intrusion is a set of actions that threaten the integrity, availability, or confidentiality of a network resource. Intrusion detection generally refers to the process of monitoring and analyzing the events occurring in a computer and/or network system in order to detect signs of security problems. Consequently, intrusion detection systems consist of software that monitors, detects, identifies, assesses, and responds to unauthorized or abnormal activities on a target system. The major functions performed by intrusion detection systems are as follows: (1) monitoring and analyzing user and system activities, (2) assessing the integrity of critical

system and data files, (3) recognizing activity patterns reflecting known attacks, (4) responding automatically to detected activities, and (5) reporting the outcome of the detection process [4]. Intrusion detection techniques can be categorized into misuse detection and anomaly detection. Misuse detection uses patterns of well-known attacks or vulnerabilities to identify intrusions. For example, three consecutive login failures may be stored and used as the signature of a password-guessing attack. However, only known attacks that leave characteristic traces can be detected this way. Anomaly detection to identify intrusions, attempts to determine whether deviations from normal usage patterns are attacks. Any significant deviations from expected behavior are reported as possible attacks. Although misuse detection can achieve a low false-positive rate, minor variations of a known attack are not always detected [5]. Anomaly detection can detect novel attacks, yet it suffers a higher false-positive rate.

A wide variety of techniques have been proposed for anomaly detection. Further analyze different kinds of data streams, such as data mining for network traffic [6], sequence analysis for operating system calls [7], information retrieval for audit trails [8], and inductive learning for sequential patterns [9]. Statistical methods have been developed for network anomaly detection [10, 11] and have been analyzed for audit records [12]. Signal processing techniques have been successfully applied to analyze network traffic logs and to filter out noise instances for network intrusion detection. In [13], a signal processing technique was shown to provide a useful detection criterion by an adaptation of mutual information when no other signature of the attack was available. Reference [14] has proposed a statistical signal processing technique based on abrupt change detection to solve the problem of anomaly detection.

Recently, an increasing amount of research has been conducted on applying neural networks to detect intrusions

[15–17]. The goal in using ANNs for intrusion detection is to be able to generalize from incomplete data and to be able to classify online data as being normal or intrusive. An ANN consists of a collection of processing elements that are highly interconnected. Given a set of inputs and a set of desired outputs, the transformation from input to output is determined by the weights associated with the interconnections among processing elements. By modifying these interconnections, the network is able to adapt to desired outputs. The ability of high tolerance for learning-by-example makes neural networks flexible and powerful in IDS. In [18], a statistical neural network classifier for anomaly detection is developed. It can identify UDP flood attacks. Comparing different neural network classifiers, the backpropagation neural network has been shown to be more efficient in developing IDS. However, a long time is required to induce models from large datasets.

Pulse code modulation (PCM) is a digital technique that involves sampling an analog signal at regular intervals and coding the measured amplitude into a series of binary values, which are transmitted by modulation of a pulsed, or intermittent, carrier. It essentially consists of three stages, namely, sampling of the analog signal, quantization, and binary encoding. During sampling, the continuously varying amplitude of the analog signal is approximated by digital values; this introduces a quantization error, the difference between the actual amplitude and the digital approximation. A quantization error is apparent when the signal is reconverted to analog form as distortion, a loss in audio quality, and it can be reduced by increasing the sample size; as allowing more bits per sample will improve the accuracy of the approximation. The approximation introduced by quantization manifests itself as a noise. Often, for the analysis of sound-processing circuits, such noise is assumed to be white and decorrelated with the signal, but in reality it is perceptually tied to the signal itself, to such an extent that quantization can be perceived as an effect. Gold and Ur [18] reported an efficient error feedback scheme for compensating the amplification of the noise generated in the comb part of complex frequency sampling FIR filters [19]. In this study, we apply the concept of signal processing to develop a training samples filter for neural networks.

3. Method

A learning machine consists of a learning protocol to specify manner of achieving accumulation of information, and a deduction procedure to learn the correct concept [17]. For a learning protocol, the input information can be examples that exemplify the concept to be learned, or oracles that, when presented with data, tell whether or not the data exemplify the concept. Therefore, we can apply not only the samples present at hand, but also extra samples produced by the oracle to train a system. When the point of query is set as y , the oracle would respond with $a(y)$. The pair $(y, a(y))$ is called the queried sample. The sample query [20] method is an incremental approach, which adaptively changes the sample size taken from each class. Particularly

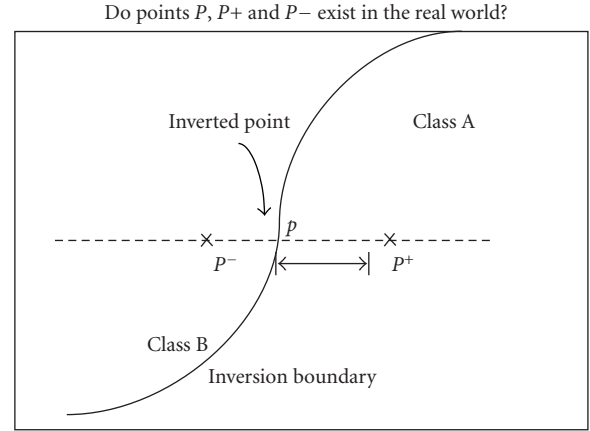


FIGURE 2: Conjugate data pairs.

in machine learning (i.e., ANNs) applications, the source of the training data can be modeled as an oracle. An oracle has the ability, when presented with an example, to give a correct classification [21]. The explanation capability of ANNs not only serves for justification but also can be useful in data theory induction, such as adding data to cover weakly represented areas by using active learning techniques, such as query-based learning [22].

In the classical problem of learning pattern classification, training samples are drawn randomly from the pattern classes according to a priori probabilities. Suppose that the learner has the freedom to query training samples according to some arbitrary rule instead of randomly drawing them, as above. According to [21, 23, 24], training samples from the decision boundary produce the best training results. We want to decide the points y to let $a(y) = 0.5$. Notably, conventional approaches have assumed that, for each input or output point, the oracle knows its input-output pattern. Random selection of a boundary point P ; then conjugation of its data pair (points P^+ and P^-) can then be extracted along the reverse boundary (Figure 2). Here, samples with P , P^+ , and P^- are arbitrary input-output patterns. However, without experts or simulators, or the oracle for specifying the correct output, this may be very expensive. To resolve this drawback, we divide the training samples into one training set and one query set. Then, an oracle is designed to follow the self-regulation rule [23] to select samples (environment-focus) that are close to the conjugate data pair (self-focus). It provides the system with the ability to interact with the environment to train the system by queried samples. As [25] has reported, the system uses some particular samples in the dataset to learn almost completely what the full dataset is taught.

In this paper, we use an oracle regarded as a compounded quantizer, which simulates the nonuniform quantization. It is designed using approximation by quantization of the filter process to achieve appropriate samples for the training procedure. Thus, learning performance is improved by labeling only those data that are expected to be informative (excluding noise). In the proposed method, we first examine

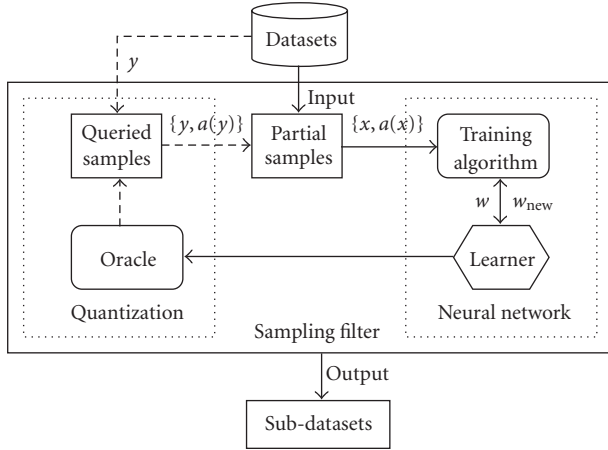


FIGURE 3: The framework of a QBS filter.

nontrained samples to detect whether they are put in the right class. As the output also indicates the probability of making a correct prediction to the samples, we can easily store these correct samples in a priority queue (max-heap). Then, the stored points that are the most correct predictions are picked as the extra training samples. Figure 3 shows the framework of a QBS filter.

A step-by-step description of the proposed algorithm is shown as follows. The learning process is finished when either the number of iterations is over the given threshold N or the root of mean squared error obtained is under the given threshold $RMSE$.

- Step 1. Initialize all weights in the neural networks randomly. Give the iteration threshold N and the error threshold $RMSE$.
- Step 2. The dataset is $S = \{a_i \in R^n\}$ where n is the number of selected attributes. Get the partial training samples $SS \subset S$ by stratified random sampling.
- Step 3. Train the neural networks by SS . IF (the error $E < RMSE$) or (the iteration number $> N$), then *EXIT*.
- Step 4. Analyze the nontrained samples ($S - SS$).
- Step 5. Add some samples of the most correct prediction to SS .

The goal of learning intrusion detection is not to obtain an exact representation of the training data but rather to extract a “model” of attack function and how it can effectively avoid those caused by noise. The ability to generalize is very important in making good predictions about unseen attacks. As in the real world, a passive learner will simply learn the samples. However, an active learner will explore the unknown portion of the environment to learn extra information. The proposed method with an ability to generalize is highly suitable for learning network intrusion. Even though the data is largely redundant and noisy. The selection of concise subsets of training data can reduce the training time.

4. Results

In this paper, we used the dataset applied in the KDD Cup 1999 intrusion detection contest to evaluate the performance

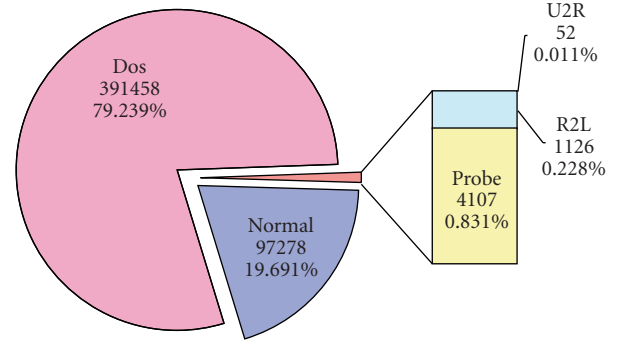


FIGURE 4: Distribution for the DARPA training set.

of our approach. This dataset is a version of the DARPA intrusion detection evaluation dataset prepared and managed by MIT’s Lincoln Laboratory. Researchers set up an environment to acquire 9 weeks of raw TCP dump data for a local-area network (LAN) simulating a typical U.S. Air Force LAN. They operated the LAN as if it were a true Air Force environment but peppered it with multiple attacks. A standard set of data to be audited, which includes a wide variety of intrusions simulated in a military network environment, was provided. Its objective was to survey and evaluate research in intrusion detection. These intrusions fall into four main categories: denial of service (DoS), probe, remote to user (R2L), and user to root (U2R). In order to compare various sampling techniques, our experiment is conducted using Weka’s implementation, a popular machine learning environment [26].

In the KDD dataset, the training set contains 494021 samples, and the test set contains 311029 samples. Figure 4 shows the data distribution of the DARPA data attack category breakdown of the training set. Nearly 80% of the samples are DoS attacks. Samples of normal connection are about 20%. Other types of attack samples, including U2R (0.011%), R2L (0.228%), and Probe (0.831%), are quite rare. It is important to note that the test data are not from the same probability distribution as the training data. The test data includes 17 specific attack types that are not in the training set. This makes the dataset more realistic. Figure 5 shows the data distribution of every attack type breakdown of the test set.

Network intrusion detection is a two-class classification problem. Its effectiveness can be defined as the ability to make correct class predictions for the samples. For each single prediction, there are four different outcomes (known as the confusion matrix in Tables 2 and 3). The true positives and true negatives are correct classifications. A false positive occurs when the system classifies an action as anomalous (a possible intrusion) when it is a legitimate action. Although this type of error may not be completely eliminated, a good system should minimize its occurrence to provide useful information to users. A false negative occurs when an actual intrusive action has occurred but the system allows it to pass as nonintrusive behavior. In other words, malicious activity is not detected and alerted. It is a more serious error. Notably,

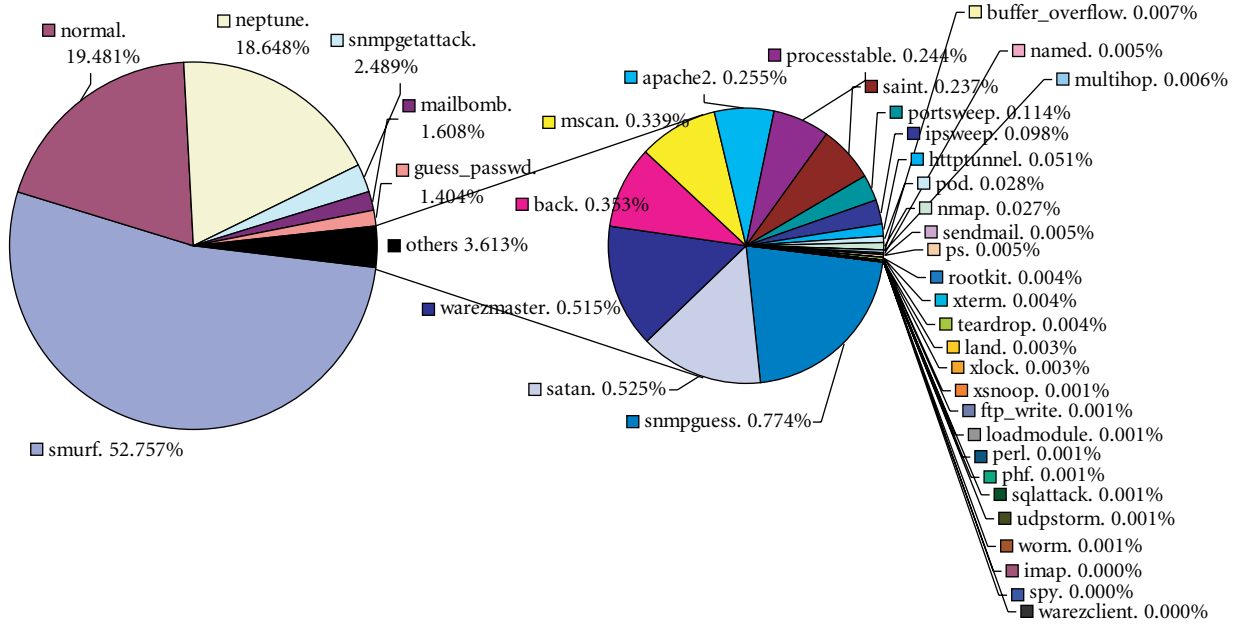


FIGURE 5: The data distribution of every attack type breakdown in the test set.

TABLE 1: Summary of results.

	Training dataset		Test dataset	
	QBS	StRS	QBS	StRS
Accuracy rate	*98.98%	98.57%	*91.55%	91.40%
Correctly classified instances	488 964	486 941	284 735	284 286
Incorrectly classified instances	5057	7080	26 294	26 743
Kappa statistic	*0.9695	0.958	*0.797	0.793
Mean absolute error	*0.0062	0.007	*0.036	0.042
Root mean squared error	*0.0595	0.071	*0.178	0.186

TABLE 2: The confusion matrix of the training dataset.

Predicted \ Actual	Normal		Probe		DoS		R2L		U2R	
	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS
Normal	93339	94000	87	683	398	96	2308	1801	846	698
Probe	42	36	4001	4056	18	1	15	9	31	5
DoS	284	2505	167	1148	390483	387763	262	34	262	8
R2L	9	15	0	0	1	0	1093	1073	23	38
U2R	0	0	0	0	0	0	4	3	48	49

TABLE 3: Detailed accuracy by class of the training dataset.

Class	TP rate		FP rate		Precision		Recall		F-measure		ROC area	
	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS
Normal	0.960	0.966	0.001	0.006	0.996	0.974	0.960	0.966	0.978	0.97	0.998	0.992
Probe	0.974	0.988	0.001	0.004	0.878	0.689	0.974	0.988	0.924	0.812	0.992	0.998
DoS	0.998	0.991	0.004	0.001	0.999	1.000	0.998	0.991	0.998	0.995	0.999	0.997
R2L	0.971	0.953	0.005	0.004	0.297	0.367	0.971	0.953	0.455	0.530	0.990	0.971
U2R	0.923	0.942	0.002	0.002	0.04	0.061	0.923	0.942	0.076	0.115	0.999	1.000

TABLE 4: The confusion matrix of the test dataset.

Predicted \ Actual	Normal		Probe		DoS		R2L		U2R	
	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS
Normal	58464	58903	992	518	256	693	546	203	335	276
Probe	471	546	3283	3284	14	84	182	171	216	81
DoS	5964	7571	30	122	222725	221899	2047	1791	689	72
R2L	13377	14219	6	0	2	0	172	140	1030	228
U2R	33	55	0	14	0	0	104	99	91	60

TABLE 5: Detailed accuracy by class of the test dataset.

	TP rate		FP rate		Precision		Recall		F-measure		ROC area	
	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS	QBS	StRS
Normal	0.965	0.972	0.079	0.089	0.747	0.725	0.965	0.972	0.842	0.830	0.973	0.978
Probe	0.788	0.788	0.003	0.002	0.762	0.834	0.788	0.788	0.775	0.810	0.916	0.968
DoS	0.962	0.959	0.003	0.010	0.999	0.997	0.962	0.959	0.980	0.977	0.969	0.982
R2L	0.012	0.010	0.010	0.008	0.056	0.058	0.012	0.010	0.020	0.016	0.293	0.372
U2R	0.399	0.263	0.007	0.002	0.039	0.084	0.399	0.263	0.070	0.127	0.623	0.957

TABLE 6: Keeping FP rate constant to demonstrate QBS outperforms StRS.

	TP rate (FP rate = 0.05)		TP rate (FP rate = 0.01)	
	QBS	StRS	QBS	StRS
Normal	0.968	0.968	0.965	0.962
Probe	0.856	0.832	0.825	0.818
DoS	0.973	0.960	0.972	0.959
R2L	0.015	0.013	0.012	0.010
U2R	0.643	0.357	0.399	0.263

in a real-world system, the effect of incorrectly detecting abnormal network behavior (false negative) is different from that of incorrectly predicting normal classification outcome (false positive). These two kinds of errors will generally have different costs; likewise, the two types of correct classification will have different benefits.

The major objectives performed by detecting network intrusion are as follows: (1) recognizing rare attack types such as U2R and R2L, (2) increasing the accuracy detection rate for suspicious activity, and (3) improving the efficiency of real-time intrusion detection models.

Extracting a model of attack from a large dataset of daily security logs is computationally inefficient. Using a sample from the original data can speed up the modeling process, but this is only acceptable if it does not reduce the quality of the information. Nevertheless, using a simple random sample may not obtain satisfactory results because such a sample may not adequately represent the large and noisy dataset due to its blind approach in selecting samples. However, we can divide a stratified sample by sampling frames into nonoverlapping groups. That is, a sample is taken from each stratum, and when this sample is a simple random sample, it is referred to as stratified random sampling. It ensures better coverage of the population than simple random sampling.

In this paper, we apply the concepts of quantization of signal processing techniques to develop a QBS filter and explore backpropagation neural networks to predict attacks. The prediction model of using QBS for neural networks is to develop a generalization capability from training data. In order to assess the predictive ability of the different models, we compared stratified random sampling (StRS) for neural networks, and we chose 500 instances as training samples from the KDD training dataset. In the first place, we examined the predicted accuracy of both estimated models by calculating the accuracy rate, Kappa statistic, mean absolute error (MAE), and root of mean squared error (RMSE). Table 1 summarizes the average classification accuracy achieved by these algorithms using 10-fold cross-validation as well as the best parameters for each algorithm. The QBS achieves a significantly better accuracy rate than the StRS approach in the training and test dataset, respectively. Moreover, as a result, the QBS is still considered to be a good fit due to the very low MAE and RMSE values.

A confusion matrix for a training dataset describes the pattern of mistakes made by the classifier (Table 2). The top-left element of the confusion matrix shows that 93339 of the QBS actual “normal” test examples were predicted to be normal. In Table 3, the precision column indicates that in total 99.6% of the actual “normal” examples were recognized correctly. The recall column shows that 96.0% of the test examples said to be “normal” were indeed “normal” in reality. Clearly, both QBS and StRS approaches produce predictive capabilities that are very close to the actual values. Note, however, that the StRS seems to perform poorly when it comes to the test cases.

This result of the confusion matrix derived from the test dataset is shown in Tables 4 and 5. The middle element of the confusion matrix shows that 222725 of the QBS actual “DoS” test examples were predicted to be DoS. In Table 5, the precision column indicates that in total 99.9% of the actual “DoS” examples were recognized correctly. The recall

column shows that 96.2% of the test examples said to be “DoS” were indeed “DoS.” Thus, QBS correctly recognized 284735 out of 311029 test examples (91.55%), and StRS correctly recognized 284286 out of 311029 test examples (91.40%). A comparison of the true-positives (TP) rate is the ratio of low weight cases predicted correctly to the total of positive cases [26] between the two models; the QBS is slightly better than the StRS. However, in this dataset, U2R and R2L are rare classes so they are major indicators to see whether and how much the QBS method and the StRS method help classifiers reduce the number of false positives and false negatives in these classes. An analysis of rare classes shows that the majority belongs to the infrequent attack types that were not in the training data. QBS achieves significantly higher correct “hits” than StRS in recognizing the U2R and R2L, respectively. In Table 6, we try to keep FP rate constant to demonstrate that QBS outperforms StRS. Experiments show that, under the same FP rate, QBS is better than StRS in TP rate for all test classes.

5. Conclusion

In this paper, we proposed that a QBS filter can apply the concepts of data quantization to signal processing to develop a novel classification system. Through interaction with a partially trained classifier, the QBS filter can efficiently use an oracle to produce high quality training data. We test the proposed method through a benchmark intrusion dataset to verify its performance and effectiveness. Results show that selecting qualified training data will have an impact on not only the performance but also the overall execution efficiency (to reduce the distortion). The proposed method can significantly increase the accuracy detection rate for suspicious activity and recognize rare attack types. Additionally, it can improve the efficiency of real-time intrusion detection models. Experiments show that the proposed method could gain effective classification. It is flexible and powerful. Intrusion detection systems must be capable of distinguishing between normal (not security critical) and abnormal user activities, to discover malicious attempts in time. However, translating user behavior (or a complete user-system session) in a consistent security-related decision is often not that simple—many behavior patterns are indistinguishable and unclear. If uncertain behavior is not considered anomalous, intrusion activity may not be detected. If uncertain behavior is considered anomalous, system administrators may be alerted by false alarms. Our future work is to extend this concept to develop more learning methods for more real-world applications.

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