Attacking Speaker Recognition with Deep Generative Models

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Abstract

In this paper we investigate targeted and untargeted attacks on speaker recognition systems. We first investigate the efficiency of SampleRNN and Wavenet in fooling GMM-UBM and CNN speaker recognizers. We design untargeted and targetted attacks based on the GAN framework. We propose a modification of the WGAN objective function to make use of data that is real but not from the class being learned. Our method if efficient in performing targetted and untargeted attacks, thus raising attention to issues related with security.

1 Introduction

Speaker recognition and authentication systems are being deployed for security critical applications such as banking, forensics, home automation, etc. Like other domains, these systems benefit from recent advancements in deep learning that lead to improved accuracy and trainability of such systems. Despite the improvement in the efficiency of these systems, evidence shows that they can be suspectible to adversarial attacks[20], thus motivating a current trend focused understanding adversarial attacks ([17], [6]) and finding countermeasures to detect of deflect them.

Parallel to these advancements, neural speech *generation* (the process of using deep neural networks to generate human-sounding speech) has also seen huge progress ([19], [2]). Generative Adversarial Networks (GANs) have recently been found to produce incredibly authentic samples in a variety of fields. The core idea of GANs - namely the minimax game played between a generator network and a discriminator network - extends very naturally to the field of speaker authentication and spoofing. The combination of these advancements begs a natural question that has, to the best of our knowledge, not been answered:

Are recent and old state-of-the-art speech recognition systems robust
to adversarial attacks by speech generative models?

More specifically, we contemplate this question and offer in this paper the following contributions:

- We evaluate SampleRNN and WaveNet in their ability to fool text-independent state-of-the-art speaker recognizers.
- We propose strategies for untargeted attacks using Generative Adversarial Networks.
- We propose strategies for targeted attacks using a new objective function based on the improved Wasserstein GAN.

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2 Related work

Generative models for speech can produce fake[1] samples that look very similar to real samples, leading humans to believe that the fake samples are real. WaveNet [18] is a generative neural network trained end-to-end to model quantized audio waveforms that has produced impressive results for conditional, speaker and text, generation of speech audio. The model is fully probabilistic and autoregressive, using a stack of causal convolutional layers to condition the predictive distribution for each audio sample on all previous ones;

SampleRNN [12], is another autoregressive architecture that has been successfully used to generate both speech and music samples. SampleRNN uses a hierarchical structure of deep RNNs to model dependencies in the sample sequence. Each deep RNN operates at a different temporal resolution so as to model both long term and short term dependencies. Another impressive model is Adobe's VoCo [1]. Although VoCo's research is unpublished, Adobe its hability to textitedit a recorded audio clip via text and make a audio clip of someone saying sentence that he never said!. Training the model requires as litle as 20 minutes of speech.

Another interesting framework for generative models are Generative Adversarial Networks (GAN) framework proposed by [5], in which a *generator* network is trained to learn a function from noise to samples that approximate the real data distribution. Simultaneously, a *discriminator* network is trained to identify whether a sample came from the real distribution or not - i.e., it is trained to try to output 1 if a sample is real, and 0 if a sample is fake. The generator and discriminator can be arbitrary networks.

In the context of deep learning architectures, adversarial examples use small perturbations to the original inputs, normally imperceptible to humans, to obtain an incorrect, target or untargeted, output from the neural network. In their brilliant papers, [17] and [6] analyze the origin of adversarial attacks and describe simple and very efficient techniques for adversarial attacks, such as the fast gradient sign method.

In the vision domain, [16] describe a technique for attacking facial recognition systems. Their attacks are physically realizable and inconspicuous, allowing an attacker to impersonate another individual. In the speech domain, [4] describe attacks on speech-recognition systems that use sounds that are hard to recognize by humans but interpreted as specific commands by speech-recognition systems.

3 Method

In this section we will describe the datasets used and the pipeline, including pre-processing and feature extraction,

3.1 Datasets

In our experiments we use three datasets, each assigned to a model as described in Table1. The datasets used are public and provide audio clips of different lengths and quality.

Table 1: Description of datasets used in our experiments. Book narr. refers to book narratives. Newspaper ++ refers to newspapers and other documents. Conversational tel. refers to conversational telephone speech.

	Speakers	Language	Duration	Context	Model
2013 Blizzard	1	English	73 h	Book narr.	SampleRNN
CSTR VCTK	109	English	400 Sentences	Newspaper ++	WaveNet
2004 NIST	100	Multiple	5 min / speaker	Conversational tel.	WGAN

3.2 Pre-processing

Data pre-processing is dependent on the model being trained. For SampleRNN and WaveNet, the raw audio is reduced to 16kHz and quantized using the $\mu - law$ companding transformation as

[1] We use the term fake to refer to computer generated samples

referenced in SampleRNN [12] and WaveNet [18]. For the model based on the Wasserstein GAN, we pre-process the data by converting it to 16kHz and removing silences by using the WebRTC Voice Activity Detector (VAD) as referenced in [21].

3.3 Feature extraction

SampleRNN and WaveNet operate at the sample level, i.e. waveform, thus requiring no feature extraction. The features used for the neural speaker recognition system is based on Mel-Spectrograms with dynamic range compression. The Mel-Spectrogram is obtained by projecting a spectrogram onto a mel scale. We use the python library librosa [11] to project the spectrogram onto 64 mel bands, with window size equal to 1024 samples and hop size equal to 160 samples, i.e. frames of 100ms long. Dynamic range compression is computed as described in [10], with $log(1 + C * M)$, where C is the a compression constant scalar set to 1000 and M is the matrix representing the Mel-Spectrogram.

4 Classification Model

4.1 Gaussian Mixture Model - Universal Background Model

4.2 Neural speaker recognition system

The speaker recognition system used in our experiments is based on the state-of-the-art framework by [10] and is described in Figure 1. The first module at the bottom is a pre-processing step that extracts Mel-Spectrograms features from the waveform as described in section 3.2. The second module is a convolutional neural network (CNN) that performs multi-speaker classification using the Mel-Spectrograms. The CNN is a modified version of Alexnet [8].

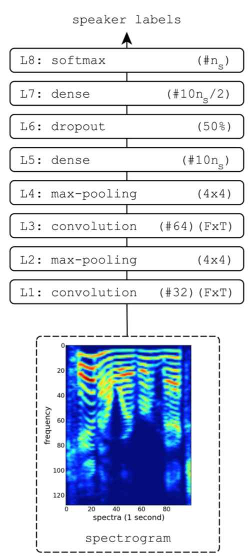


Figure 1: Architecture for CNN speaker verifier

We train the CNN on our training set using 64*64 Mel-Spectrograms [2] consisting of balanced samples from 101 speakers from the NIST 2004 and Blizzard datasets. Our model achieves 85% test set accuracy.

[2] 64 mel bands and 64 frames, 100 ms each

5 Generative Model

5.1 WaveNet

WaveNet is a generative neural network trained end-to-end to model quantized audio waveforms. It has produced impressive results for conditional, speaker and text, generation of speech audio. The model is fully probabilistic and autoregressive, using a stack of causal convolutional layers to condition the predictive distribution for each audio sample on all previous ones;

5.2 SampleRNN

SampleRNN [12], another autoregressive architecture that has been successfully used to generate both speech and music samples. SampleRNN uses a hierarchical structure of deep RNNs to model dependencies in the sample sequence. Each deep RNN operates at a different temporal resolution so as to model both long term and short term dependencies.

5.3 Wasserstein GANs

In the original generative adversarial network (GAN) framework proposed by [5], a *generator* network is trained to learn a function from noise to samples that approximate the real data distribution. Simultaneously, a *discriminator* network is trained to identify whether a sample came from the real distribution or not - i.e., it is trained to try to output 1 if a sample is real, and 0 if a sample is fake. The generator and discriminator can be arbitrary networks.

The GAN framework has been shown to be able to produce very realistic samples with low training overhead. However, since the generator is trained to minimize the Kullback-Leibler (KL) divergence between its constructed distribution and the real one, it suffers from an exploding loss term when the real distribution's support isn't contained in the constructed one. To counter this, the *Wasserstein GAN* [3] (WGAN) framework instead uses the Wasserstein (Earth-Mover) distance between distributions instead, which in many cases does not suffer from the same explosion of loss and gradient. Based on this, the loss functions of the generator and *critic* (which no longer emits a simple probability, but rather an approximation of the Wasserstein distance between the fake distribution and real) become:

$$L_G = -\mathop{\mathbb{E}}_{\tilde{\boldsymbol{x}} \sim \mathbb{P}_g}\big[D(\tilde{\boldsymbol{x}})\big] \tag{1}$$

$$L_C = \mathop{\mathbb{E}}_{\tilde{\boldsymbol{x}} \sim \mathbb{P}_g}\big[D(\tilde{\boldsymbol{x}})\big] - \mathop{\mathbb{E}}_{\boldsymbol{x} \sim \mathbb{P}_r}\big[D(\boldsymbol{x})\big] \tag{2}$$

where P_r is the real distribution, and P_g the learnt distribution of the generator.

The original WGAN framework uses weight clipping to ensure that the critic satisfies a Lipschitz condition. As pointed by [7], however, this clipping can lead to problems with gradient stability. Instead, [7] suggest adding a gradient penalty to the critic's loss function, which indirectly tries to constrain the original critic's gradient to have norm close to 1. Equation (2) thus becomes (taken from [7]):

$$L_C = \underbrace{\mathop{\mathbb{E}}_{\tilde{\boldsymbol{x}} \sim \mathbb{P}_g}\big[D(\tilde{\boldsymbol{x}})\big] - \mathop{\mathbb{E}}_{\boldsymbol{x} \sim \mathbb{P}_r}\big[D(\boldsymbol{x})\big]}_{\text{Original critic loss}} + \underbrace{\lambda \mathop{\mathbb{E}}_{\hat{\boldsymbol{x}} \sim \mathbb{P}_{\hat{\boldsymbol{x}}}}\big[(\|\nabla_{\hat{\boldsymbol{x}}} D(\hat{\boldsymbol{x}})\|_2 - 1)^2\big]}_{\text{Gradient Penalty}} \tag{3}$$

5.4 Adversarial attacks

Attacks to classification systems can be targeted or untargeted. In targeted attacks, an adversary is interested in producing an adversarial input that makes the classification system predict a target class. In untargeted attacks, the adversary is interest in a confident prediction, regardless of the class.

6 Results on existing methods

We used the samples produced with WaveNet and SampleRNN, as well as Mel-Spectrograms generated with improved WGAN, to perform adversarial attacks to the neural speaker recognition system.

6.1 WaveNet

We attempted to replicate the model described in [18] but, unfortunately, we do not have access to Google's computing power nor to the North American Speech dataset Google used to train the WaveNet model that produced the samples referenced in [18]. Nonetheless, we used the data from CSTR VCTK to train speaker dependent WaveNet speech synthesis model that converged to producing speech that resembled the speakers voice but sounded like babbling.

6.2 sampleRNN

We also tested samples from sampleRNN [12], another autoregressive architecture that has been successfully used to generate both speech and music samples. SampleRNN uses a hierarchical structure of deep RNNs to model dependencies in the sample sequence. Each deep RNN operates at a different temporal resolution so as to model both long term and short term dependencies. We generated samples from the three-tiered variant, trained on the Blizzard 2013 dataset [14], a 300 hour corpus of a single female speaker's narration. We also downloaded 10 second samples from the original paper's online repository at `https://soundcloud.com/samplernn/sets`, which we qualitatively found to have less noise than our generated ones.

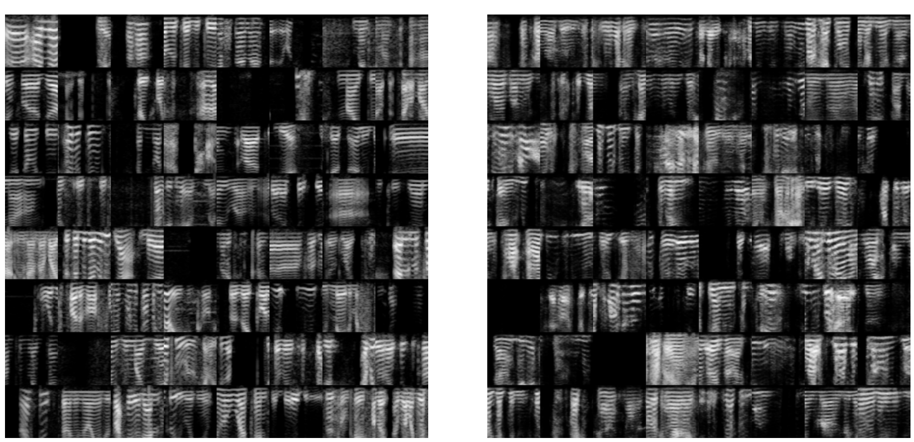
7 Results on adversarial methods

7.1 GAN Mel-Spectrogram Results

We trained this form of the GAN to construct 64x64 Mel-Spectrogram images from noise. We used two popular models for ConvNet image generation for the generator/discriminator architecture:

- *DCGAN* [15] models the generator as a series of deconvolutional layers with ReLU activations, and the discriminator as a series of convolutional ones with leaky ReLU activations. Both architectures use batch normalization after each layer.
- *ResNet* [9] GAN models the generator and discriminator each as very deep convnets (30 layers in our experiments) with upsampling/downsampling respectively. Residual (skip) connections are added every few layers to make training easier.

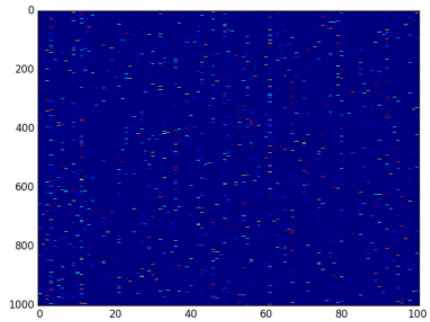
Visual results are demonstrated below. We generally used the same parameters as the [7] paper, namely 5 critic iterations per generator iteration, a gradient penalty weight of 10, and batch size of 64. We saw recognizable spectrogram-like features in the data after only 1000 generator iterations, and after 5000 the generated samples were indistinguishable from real ones. Training took around 10 hours for 20000 iterations on a single 4 GB Nvidia GK104GL GPU.



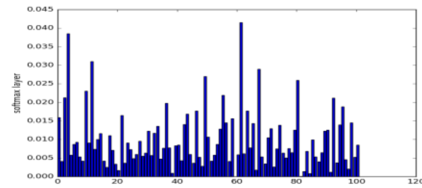
(a) Actual

(b) Generated

Figure 2: Comparison of real and generated ($\sim$ 5000 generator iterations) spectrogram samples. Each grid contains 64 samples.



(a) activation of fully-connected layer (L2) on randomly sampled speech



(b) distribution of randomly sampled speech from the generative model

Figure 3: Summary of Untargeted Attacks

7.2 Adversarial attacks

Within the GAN framework, untargeted models are trained by using all data available, irrespective of class label. We show that an untargeted model able to generate data from the real distribution of the data and with enough variety can be used to perform adversarial attacks by classifying the samples produced by the generator. We provide details in the Untargeted attacks subsection. The models for targeted attacks can be trained in two manners. The first is based on conditioning the model on additional information, e.g. class labels, as described in [13]. The second is based on using only data from the label of interest. A drawback of the second approach is that the discriminator, and by consequence the generator, does not have access to universal[3]. properties of speech. To circumvent this problem, we propose a new objective function that allows using the data from all classes, although the generator is learning how to generate one class.

7.2.1 Untargeted attacks

For each of the speech in test set, we use the Mel-Spectrogram algorithm in section 3.2 to transform them into Mel-Spectrograms. The resulting mel-spectrogram is then fed into the CNN verifier and we extract a 505-dimensional feature G from the penultimate fully-connected layer (L7) in the pre-trained CNN model (1) trained on the real speech dataset with all speaker ID. The deep feature G is then used to train a K-nearest-neighbor (KNN) classifier.

To control the generator trained by our WGAN, we feed the generated Mel-Spectrograms into the same CNN-L2 pipeline to extract their corresponding feature $\widehat{G}$. Utilizing the pre-trained KNN, each sample is assigned to the nearest speaker in the deep feature space. Therefore, we know which speaker our generated sample belongs to when we attack our CNN verifier. We evaluate our controlled WGAN samples against the state-of-the-art CNN verifier, and the confusion matrix can be found in Figure 4a. Although not included in the figure, **neither WaveNet samples nor SampleRNN samples were able to attack the recognition model in the same way.** [4]

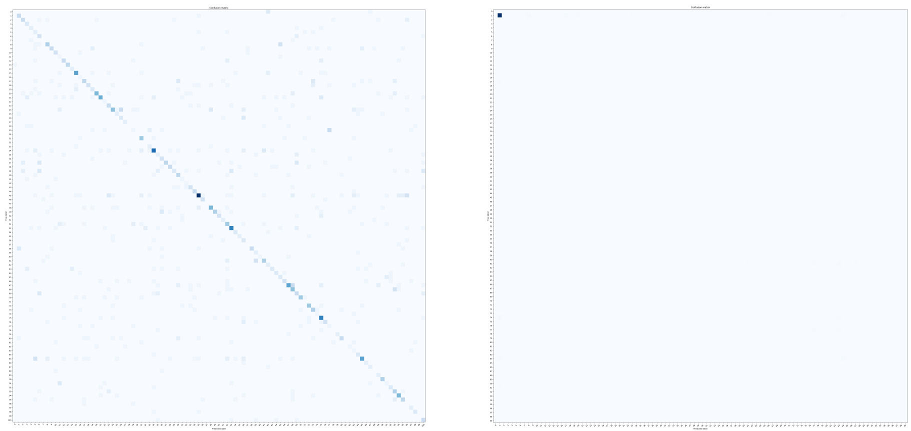
Figure 3b depicts that our GAN-trained generator successfully learns all speakers across the dataset, without mode collapsing.

7.2.2 Targeted attacks

However, the most natural attack is one in which we train a GAN to directly fool a speaker-authentication system, i.e., to produce samples that the system classifies as matching a target speaker with reasonable confidence. To train our WGAN in this way, we propose a modification to the critic that allows it to learn differentiate between not only real samples and generated samples, but also between real speech samples from a target speaker and real speech samples from other speakers. We do this by adding a term to the critic's loss that encourages its discriminator to classify real speech

[3] We draw a parallel with Universal Background Models in speech

[4] We also use the old state-of-the-art GMM-UBM speaker verifier.



(a) Confusion matrix of targeted attacks using untargeted model

(b) Confusion matrix of targeted attacks using targeted model

Figure 4: Confusion matrix of targeted attacks

samples from untargeted speakers as fake. The critic's loss L_C becomes:

$$\underbrace{\underset{\tilde{\boldsymbol{x}}\sim\mathbb{P}_g}{\mathbb{E}}\left[D(\tilde{\boldsymbol{x}})\right]}_{\text{Generated Samples}} \underbrace{+\alpha * \underset{\dot{\boldsymbol{x}}\sim\mathbb{P}_{\dot{x}}}{\mathbb{E}}\left[D(\dot{\boldsymbol{x}})\right]}_{\text{Different Speakers}} - \underbrace{\underset{\boldsymbol{x}\sim\mathbb{P}_r}{\mathbb{E}}\left[D(\boldsymbol{x})\right]}_{\text{Real Speaker}} + \underbrace{\lambda \underset{\hat{\boldsymbol{x}}\sim\mathbb{P}_{\hat{x}}}{\mathbb{E}}\left[(\|\nabla_{\hat{\boldsymbol{x}}} D(\hat{\boldsymbol{x}})\|_2 - 1)^2\right]}_{\text{Gradient Penalty}} \tag{4}$$

where $P_{\hat{x}}$ is the distribution of samples from other speakers, and α is a tunable scaling factor. In our experiments, we trained this GAN with 1 target speaker and a set of 99 'other' speakers. On each of the critic, we would feed the critic a batch of samples from one target speaker, and a batch of data uniformly sampled from the other speakers. We used an α of 0.1 (we found that not including this scaling factor led to serious the critic seriously overfitting and poor convergence of the GAN). Results are demonstrated in figure 4 b): The confusion matrix demonstrates all energy is concentrated in speaker id 2.

8 Discussion and Conclusion

In this paper we have investigated the use of speech generative models to perform adversarial attacks on speaker recognition systems. We show that the autoregressive models we trained, i.e. SampleRNN and WaveNet, were not able to fool the GMM-UBM and CNN speaker recognizers we built. On the other hand, we show that adversarial examples generated with GAN networks are successful in performing targeted and untargeted adversarial attacks. A pertinent argument against the validity of the GMM-UBM tests lies on the fact that GMM-UBM models have high precision and would not generalize to speech in different conditions, e.g. different room and microphone conditions. First, it is not within the scope of this paper to build a speaker recognition system that is invariant to room and microphone conditions. Second, given that the speaker recognition models, GMM-UBM and CNN, have good performance on test data and that WaveNet and SampleRNN goal is to replicate speech data that is from a speaker with similar and fixed microphone and room conditions, it is expected that the outputs of these generative models should be properly classified by the speaker recognition system.

On the other hand, we show that targeted and untargeted adversarial attacks with the GAN framework are efficient on the CNN speaker classifier trained by us. With this paper we hope to raise attention to issues that generative models bring to security and biometric systems. We foresee that samples produced with generative models have a signature that can be used to identify the source of the data and leave this investigation for future work.

Acknowledgments

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