Joint magnitude estimation and phase recovery using Cycle-in-Cycle GAN for non-parallel speech enhancement

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Summary

- We propose a novel system, dubbed Cycle-in-Cycle GAN, to handle speech enhancement when the training noisy-clean data pairs are mismatched.
- Inspired by the decoupling-style concept, we decouple the difficult target *w.r.t.* original spectrum optimization and use two CycleGANs to jointly estimate the spectral magnitude and phase information in a stage-wise manner.
- In the first stage, we pretrain a magnitude CycleGAN to coarsely estimate the spectral magnitude of clean speech. In the second stage, we incorporate the pretrained CycleGAN with a complex-valued CycleGAN as a cycle-in-cycle structure.
- Experimental results demonstrate that the proposed approach significantly outperforms previous baselines under nonparallel training.

Introduction

Non-parallel single-channel speech enhancement:

- Standard DNN-based supervised SE approaches always need numerous paired clean-noisy samples to conduct supervised training and improve the generalization.
- In some real scenarios, it is troublesome to record parallel clean-noisy pairs, and we can only obtain clean speech that mismatches the source noisy speech.
- cycle-consistent GAN (CycleGAN) has been developed to conduct unsupervised SE by using adversarial loss, cycleconsistency loss and identity-mapping loss.
- Due to the severe mismatch between input and target, previous CylceGAN based methods only focus on magnitude spectrum estimation and remain the noisy phase unaltered.

Cycle-in-Cycle GAN for non-parallel SE



(a) forward noisy-clean-noisy cycle



• As Figure. 1(a) and (b) show, the proposed CinCGAN consists of a forward noisy-clean-noisy cycle and a backward cleannoisy-clean cycle. In the forward cycle, the enhancement procedure can be divided into two steps. First, we decouple the complex spectrum into spectral magnitude and phase, and only the amplitude is processed. Subsequently, the estimated spectral magnitude and the original phase are fed it into CCGAN to estimate both real and imaginary parts.



(b) Complex generator

- As Figure 2(a) and (b) illustrate, both magnitude and complex generators adopt convolutional encoder-decoder topology, and multiple adaptive time-frequency attention (ATFA) modules and an adaptive hierarchical attention (AHA) module are inserted for temporal modeling.
- In the first step, we pretrain MCGAN alone with the same relativistic adversarial loss, cycle-consistency loss, and identity mapping loss until convergence. Then, we jointly fine-tune MCGAN and CCGAN with the same losses, which can be expressed as:

 $\mathcal{L}_{MCGAN} = \mathcal{L}_{Radv}(G_{X \to Y}^{mc}, D_Y^{mc}) + \mathcal{L}_{Radv}(F_{Y \to X}^{mc}, D_X^{mc})$ $+\lambda_{cycle}\mathcal{L}_{cycle}(G_{X\to Y}^{mc}, F_{Y\to X}^{mc}) + \lambda_{id}\mathcal{L}_{id}(G_{X\to Y}^{mc}, F_{Y\to X}^{mc})$

Figure 1: System flowchart of CinCGAN. The magnitude and complex cycle are shown in the yellow and blue dotted boxes, respectively.

Figure 1: (a) The diagram of the magnitude generators in MCGAN. (b) The diagram of the complex generators in CCGAN.

Experiments

- **Datset:**

Implementation Setup

Comparison results & analysis

(1)

Guochen Yu^{1,2}, Andong Li², Yutian Wang¹, Yinuo Guo³, Hui Wang¹, Chengshi Zheng²

• The dataset we chosen is a selection of the Voice Bank corpus with 28 speakers for training and another 2 unseen speakers for testing

• The training set consists of 11,572 mono audio samples, while the test set contains 824 utterances. • For the training set, audio samples are mixed together with one of the 10 noise types (*i.e.*, two artificial and eight real noise from the DEMAND database. The testing utterances are created with 5 unseen test-noise types from the DEMAND.

• The Hanning window of length 32ms is applied, with 75% overlap between adjacent frames. The 512-point STFT is utilized, leading to a 257-D spectral feature.

• We conduct the power compression toward the spectral magnitude while leaving the phase unaltered, and the optimal compression coefficient is set to 0.5.

• We randomly crop a fixed-length segment (*i.e.*, 108 frames) from a randomly selected noisy audio file as the input, while the target is a randomly selected clean audio file which is different from the input audio. • The training process is divided in two steps and the overall loss function can be expressed as:

 $\mathcal{L}_{CinCGAN} = \gamma \mathcal{L}_{MCGAN} + \mathcal{L}_{CCGAN}$

| Table 1: Experimental results among different models under unpaired data. | | | | | | | | | | | | | |
|---|---------------|----------------------|--------------|---------------|--------------|--------------|--------------|----------------------|---------------|-------------|--------------|--------|--------|
| Methods Feature type | | re type | Magnitude | | Complex | | – PESO | STOI(%) | CSIG | CBAK | COVL | SegSNR | DNSMOS |
| Linnacocod | | JI | fC | bc | fC | bc | | 02 1 | 2.25 | 7 44 | 762 | 1.60 | 2 02 |
| Unprocessed | | - J- b ase | 1.97 | 92.1 | 5.55 | 2.44 | 2.03 | 1.00 | 3.02 | | | | |
| MGAN | Magn | itude | × | X | | | 203 | 91.6 | 3 54 | 2 78 | 2 72 | 5 28 | 2 72 |
| MGAN+fc | Magn | itude | | × | | X | 2.58 | 92.8 | 3.81 | 3.03 | 3.19 | 5.28 | 3.26 |
| CGAN | RI con | nponents | | X | | X | 1.86 | 88.9 | 3.17 | 2.62 | 2.64 | 2.98 | 2.63 |
| CGAN+fc | RI con | nponents | × | × | \checkmark | × | 2.32 | 91.2 | 3.48 | 2.74 | 3.18 | 4.67 | 3.04 |
| Proposed CycleGAN-based Systems | | | | | | | | | | | | | |
| MCGAN Magnitude | | | \checkmark | \checkmark | X | × | 2.67 | 93.2 | 3.86 | 3.20 | 3.21 | 7.23 | 3.47 |
| CCGAN | RI components | | × | × | \checkmark | \checkmark | 2.56 | 92.1 | 3.67 | 3.10 | 3.16 | 5.38 | 3.42 |
| CinCGAN (I) | Magn | itude + RI | \checkmark | × | \bigvee | × | 2.70 | 93.4 | 3.93 | 3.24 | 3.25 | 7.34 | 3.44 |
| CinCGAN (II) | Magn | itude + RI | \checkmark | \checkmark | \checkmark | X | 2.77 | 93.6 | 3.96 | 3.02 | 3.30 | 4.49 | 3.49 |
| CinCGAN (III) | Magn | itude + RI | | × | | \checkmark | 2.73 | 93.5 | 3.94 | 3.27 | 3.29 | 7.98 | 3.51 |
| CinCGAN (IV) | Magn | itude + RI | \checkmark | \checkmark | \checkmark | \checkmark | 2.84 | 94.1 | 4.10 | 3.36 | 3.37 | 8.91 | 3.53 |
| Table 2: Comparison with other GAN and Non-GAN based systems under standard paired data | | | | | | | | | | | | | |
| | Methods | | • | Feature | | | PESQ | STOI(%) | CSIG | CBAK | COVL | | |
| Unproces | | ssed | _ | | | 1.97 | 92.1 | 3.35 | 2.44 | 2.63 | | | |
| GAN-based Systems | | | | | | | | | | | | | |
| | SEGAN | | | Wavefo | orm | | 2.16 | 92.5 | 3.48 | 2.94 | 2.80 | | |
| | MMSEG | | AN | N Gamm | | | 2.53 | 93.0 | 3.80 | 3.12 | 3.14 | | |
| SERGAN | | J | Wavefo | orm | | 2.51 | 93.7 | 3.78 | 3.23 | 3.16 | | | |
| | CP-GAN | | | Wavefo | orm | | 2.64 | 94.0 | 3.93 | 3.29 | 3.28 | | |
| | MetricGA | | AN | Magni | tude | | 2.86 | — | 3.99 | 3.18 | 3.42 | | |
| | CRGAN | | . . | Magni | ude | | 2.92 | 94.0 | 4.16 | 3.24 | 3.54 | | |
| SASEGA | | N | Wavefo | orm | | 2.36 | 93.5 | 3.54 | 3.08 | 2.93 | | | |
| Non-GAN based Systems | | | | | | | | | | | | | |
| Wave-U-ne | | | | et Wavefo | | | 2.64 | — | 3.56 | 3.08 | 3.09 | | |
| DFL-SE | | | | Wavefo | | | - | - | 3.86 | 3.33 | 3.22 | | |
| CRN-MS | | | E Magnit | | tude | | 2.61 | 93.8 | 3.78 | 3.11 | 3.24 | | |
| GCKN | | | | | iponents | | 2.51 | 94.0 | 3.71 | 3.24 | 3.09 | | |
| | | | | ponents | | 2.68 | 93.9 | 3.88 | 3.18 | 3.27 | | | |
| | TFSNN | | | Waveform | | | 2./9 | - | 4.17 | 3.27 | 3.49 | | |
| | | | - | Proposed Cycl | | | AIN-based | approaches | 5 | 2 05 | 2 00 | | |
| | | | Magnit | | tuae | | 2./4 | 93.6 0 2 8 | 3.96 | <i>3.25</i> | 3.29 | | |
| | CCGAN | | NT | KI comp | | | 2.6U 2.06 | 92.8 04 4 | 3.82 1 1 0 | 3.12 | 3.2U 2.40 | | |
| | CinCGAI | | | | | IXI | 2.80 | 74.4 | 4.1ð | 3.38 | 3.42 | | |
| | | | | | | | | | | | | | |

| | Table 1. Expe | | | | | 5 uniere | | unueru | ilpaileu | uala. | | |
|------------|-----------------|-------------------------|-----------------|--------------|---------------------|-------------------|-------------|-------------|------------------------------|----------------------------|---------|--------|
| hods Fea | Feature type | fc | bc | fc | hplex | PESQ | STOI(%) | CSIG | CBAK | COVL | SegSNR | DNSMOS |
| processed | | | _ | | _ | 1.97 | 92.1 | 3.35 | 2.44 | 2.63 | 1.68 | 3.02 |
| | | | | GAN | -base | d method | S | | | | | |
| AN | Magnitude | × | X | × | X | 2.03 | 91.6 | 3.54 | 2.78 | 2.72 | 5.28 | 2.72 |
| AN+fc | Magnitude | \checkmark | × | × | X | 2.58 | 92.8 | 3.81 | 3.03 | 3.19 | 5.28 | 3.26 |
| AN | RI components | \times | × | × | X | 1.86 | 88.9 | 3.17 | 2.62 | 2.64 | 2.98 | 2.63 |
| AN+fc | RI components | \times | × | \checkmark | × | 2.32 | 91.2 | 3.48 | 2.74 | 3.18 | 4.67 | 3.04 |
| | 1 | 1 | Propos | ed Cy | cleGA | N-based | Systems | | | | | |
| GAN | Magnitude | \checkmark | \checkmark | × | X | 2.67 | 93.2 | 3.86 | 3.20 | 3.21 | 7.23 | 3.47 |
| GAN | RI components | \times | × | \checkmark | \checkmark | 2.56 | 92.1 | 3.67 | 3.10 | 3.16 | 5.38 | 3.42 |
| CGAN (I) | Magnitude + RI | \checkmark | × | \checkmark | X | 2.70 | 93.4 | 3.93 | 3.24 | 3.25 | 7.34 | 3.44 |
| CGAN (II) | Magnitude + RI | \checkmark | \checkmark | \checkmark | X | 2.77 | 93.6 | 3.96 | 3.02 | 3.30 | 4.49 | 3.49 |
| CGAN (III) | Magnitude + RI | \checkmark | × | \checkmark | \checkmark | 2.73 | 93.5 | 3.94 | 3.27 | 3.29 | 7.98 | 3.51 |
| CGAN (IV) | Magnitude + RI | \checkmark | \checkmark | \checkmark | \checkmark | 2.84 | 94.1 | 4.10 | 3.36 | 3.37 | 8.91 | 3.53 |
| Table 2: | Comparison wi | th of | her GA | N and | 1 No | n-GAN | pased syst | ems und | er stand | ard pairs | ed data | |
| | Mothoda | | Footur | | | PESO | | | | | | |
| | Lipproco | o nond | i cature type | | | 1.07 | 02.1 | 2.25 | $\frac{\mathbf{CDAK}}{2.44}$ | $\frac{\text{COVL}}{2.62}$ | | |
| | | | | Nha | $\frac{1.97}{2000}$ | 92.1 | 5.55 | 2.44 | 2.03 | | | |
| | SECAN | | Manofe | GA | | $\frac{5eu}{216}$ | 02 5 | 2 / 8 | 2.0/ | 2.80 | | |
| | JEGAN MMSEC | JEGAIN MMSECANI | | | | 2.10 | 92.3 | 3.40 | 2.9 4 3.19 | 2.00 | | |
| | SERCAN | IVIIVIJEGAIN SEDCANI | | | | 2.55 | 93.0 | 3.78 | 3.12 | 3.14 | | |
| | $CP_C \Delta N$ | CP_CAN | | | | 2.51 2.64 | 94.0 | 3.70 | 3.20 | 3.10 | | |
| | MotricCa | ANT | Magnit | | | 2.01 | - | 3.90 | 3.18 | 3.42 | | |
| | CRCAN | CRCAN | | Magnitude | | 2.00 2 92 | 94.0 | <i>4</i> 16 | 3.10 | 3.54 | | |
| | SASEGA | SASEGAN | | Waveform | | 2.92 | 93 5 | 3 54 | 3.08 | 2.9 1 | | |
| | | | | | GAN ⁻ | based Sv | stems | 0.01 | 0.00 | 2.70 | | |
| | Wave-U- | net | Wavefo | nrm | | 2 64 | _ | 3 56 | 3.08 | 3 09 | | |
| | DEL-SE | | | | | 2.01 | _ | 3.86 | 3 33 | 3.02 | | |
| | CRNLMS | CRNLMSF | | Magnitudo | | 2 61 | 93.8 | 3.78 | 3.11 | 3.22 | | |
| | GCRN | RI components | | | 2.01 | 94.0 | 3 71 | 3.24 | 3.09 | | | |
| | DCCRN | RI components | | | 2.61 | 93.9 | 3.88 | 3.18 | 3 27 | | | |
| | TESNN | Waveform | | | 2.00 | _ | 4 17 | 3.27 | 3 49 | | | |
| | | | Proposed CycleC | | cleG/ | N-based | approache | S | 0.27 | 0.17 | | |
| | MCGAN | <u></u> | Magnif | tude | | 2 74 | <u>93.6</u> | 396 | 3 25 | 3 29 | | |
| | CCCAN | I | RI components | | nts | 2.60 | 92.8 | 3.82 | 3.12 | 3.20 | | |
| | CinCGA | N | Magnitude+ RI | | | 2.86 | 94.4 | 4.18 | 3.38 | 3.42 | | |
| | | | 0 | | I | | | | | | | |

| atura tura | Magnitude | | Com | olex | | STOI(0/) | CCIC | | COM | CARCNID | |
|--|---------------------|---|--|--|---|---|--|--|--|---------|----------|
| ature type | fc | bc | fc | bc | | 5101(%) | CSIG | UDAK | CUVL | SegSINK | DINSIMOS |
| _ | _ | _ | | | 1.97 | 92.1 | 3.35 | 2.44 | 2.63 | 1.68 | 3.02 |
| | • | | GAN- | base | d method | S | | | | | |
| agnitude | × | X | \times × | | 2.03 | 91.6 | 3.54 | 2.78 | 2.72 | 5.28 | 2.72 |
| agnitude | \checkmark | × | × | \times | 2.58 | 92.8 | 3.81 | 3.03 | 3.19 | 5.28 | 3.26 |
| components | \times | × | × | \times | 1.86 | 88.9 | 3.17 | 2.62 | 2.64 | 2.98 | 2.63 |
| components | \times | × | \checkmark × | | 2.32 | 91.2 | 3.48 | 2.74 | 3.18 | 4.67 | 3.04 |
| | | Propos | sed Cyc | leGA | N-based | Systems | | | | | |
| agnitude | \checkmark | \checkmark | × | × | 2.67 | 93.2 | 3.86 | 3.20 | 3.21 | 7.23 | 3.47 |
| components | \times | × | \checkmark | \checkmark | 2.56 | 92.1 | 3.67 | 3.10 | 3.16 | 5.38 | 3.42 |
| agnitude + RI | \checkmark | × | \checkmark | \times | 2.70 | 93.4 | 3.93 | 3.24 | 3.25 | 7.34 | 3.44 |
| agnitude + RI | \checkmark | \checkmark | \checkmark | \times | 2.77 | 93.6 | 3.96 | 3.02 | 3.30 | 4.49 | 3.49 |
| agnitude + RI | \checkmark | × | \checkmark | \checkmark | 2.73 | 93.5 | 3.94 | 3.27 | 3.29 | 7.98 | 3.51 |
| agnitude + RI | \checkmark | \checkmark | \checkmark | \checkmark | 2.84 | 94.1 | 4.10 | 3.36 | 3.37 | 8.91 | 3.53 |
| mnarison wi | th ot | her GA | N and | Not | n-GAN I | nased syste | oms und | er stand | ard paire | d data | |
| Mathada | | | | | | | | | | | |
| Internous | | | reature type | | 1 07 | <u>3101(/0)</u> | 2.25 | | | | |
| Unprocessed – | | | | | 1.97 | 92.1 | 5.55 | 2.44 | 2.03 | | |
| | | Manof | GAN | $\frac{\text{GAIN-Daseu Systems}}{2.16 \qquad 0.25 \qquad 2.48 \qquad 2.04 \qquad 2.80}$ | | | | | | | |
| JEGAIN MMSEC | ANT | Commotopo | | | 2.10 | 92.3 | 5.40 2.80 | 2.9 4 2.10 | 2.00 2.17 | | |
| SEDCAN | T T | Wayoform | | | 2.55 | 93.0 | 3.00 | $\begin{array}{c} 3.1 \\ 3.1 \\ \end{array}$ | 3.1 4 3.16 | | |
| SERGAN V | | Waveform | | | 2.51 | 93.7 | 5.76 | 3.23 | 3.10 | | |
| CPCAN | CP-GAN W | | α | | | | '2 U 2 | | | | |
| CP-GAN | A NT | Wavef | orm | | 2.64 | 94.0 | 3.93 | 3.29 2.10 | 2.40 | | |
| CP-GAN MetricGA | AN | Magni Magni | orm tude | | 2.64 2.86 | 94.0 - 04.0 | 3.93 3.99 4.16 | 3.29 3.18 2.24 | 3.42 3.42 | | |
| CP-GAN MetricGA CRGAN | AN N | Wavef Magni Magni | orm tude tude | | 2.64 2.86 2.92 2.36 | 94.0 - 94.0 02.5 | 3.93 3.99 4.16 3.54 | 3.29 3.18 3.24 3.08 | 3.42 3.54 2.03 | | |
| CP-GAN MetricGA CRGAN SASEGA | AN N | Wavef Magni Magni Wavef | orm tude tude orm Non-C | | 2.64 2.86 2.92 2.36 | 94.0 - 94.0 93.5 | 3.93 3.99 4.16 3.54 | 3.29 3.18 3.24 3.08 | 3.42 3.54 2.93 | | |
| CP-GAN MetricGA CRGAN SASEGA | AN N | Wavefe Magni Magni Wavefe | orm tude tude orm Non-G | | 2.64 2.86 2.92 2.36 based Sys | 94.0 94.0 93.5 stems | 3.93 3.99 4.16 3.54 | 3.29 3.18 3.24 3.08 | 3.42 3.54 2.93 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U-2 | AN N net | Wavefe Magni Magni Wavefe Wavefe | orm tude tude orm Non-G orm | AN 1 | 2.64 2.86 2.92 2.36 based Sys 2.64 | 94.0 94.0 93.5 stems | 3.93 3.99 4.16 3.54 3.54 | 3.29 3.18 3.24 3.08 3.08 | 3.42 3.54 2.93 3.09 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U-2 DFL-SE | AN N net | Wavefe Magni Magni Wavefe Wavefe | orm tude tude orm Non-G orm orm | <u>AN</u>] | 2.64 2.86 2.92 2.36 based Sys 2.64 | 94.0 94.0 93.5 stems - | 3.93 3.99 4.16 3.54 3.56 3.86 2.79 | 3.29 3.18 3.24 3.08 3.08 3.33 2.11 | 3.42 3.54 2.93 3.09 3.22 2.94 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U-2 DFL-SE CRN-MS | AN N net E | Wavefe Magni Magni Wavefe Wavefe Magni | orm tude tude orm Non-G orm orm tude | | 2.64 2.86 2.92 2.36 based Sys 2.64 - 2.61 2.61 | 94.0 94.0 93.5 stems - 93.8 93.8 | 3.93 3.99 4.16 3.54 3.54 3.56 3.86 3.78 2.71 | 3.29 3.18 3.24 3.08 3.08 3.33 3.11 2.24 | 3.42 3.54 2.93 3.09 3.22 3.24 2.00 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U-2 DFL-SE CRN-MS GCRN | AN N net E | Wavefe Magni Magni Wavefe Wavefe Magni RI com | orm tude tude orm Non-G orm orm tude ponent | AN 1 | 2.64 2.86 2.92 2.36 based Sys 2.64 2.61 2.51 2.69 | 94.0 94.0 93.5 Stems - 93.8 94.0 02.0 | 3.93 3.99 4.16 3.54 3.54 3.56 3.86 3.78 3.71 2.89 | 3.29 3.18 3.24 3.08 3.08 3.33 3.11 3.24 2.19 | 3.42 3.54 2.93 3.09 3.22 3.24 3.09 2.97 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U- DFL-SE CRN-MS GCRN DCCRN | AN N net E | Wavefe Magni Magni Wavefe Wavefe Magni RI com RI com | orm tude tude orm Non-G orm orm tude ponent | AN 1 s s | 2.64 2.86 2.92 2.36 based Sys 2.64 - 2.61 2.51 2.68 | 94.0 94.0 93.5 stems - 93.8 94.0 93.9 | 3.93 3.99 4.16 3.54 3.54 3.56 3.86 3.78 3.71 3.88 | 3.29 3.18 3.24 3.08 3.08 3.33 3.11 3.24 3.18 | 3.42 3.54 2.93 3.09 3.22 3.24 3.09 3.27 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U-2 DFL-SE CRN-MS GCRN DCCRN TFSNN | AN N net E | Wavefe Magni Magni Wavefe Wavefe Magni RI com RI com Wavefe | orm tude tude orm Non-G orm orm tude ponent ponent | AN S S | 2.64 2.86 2.92 2.36 based Sys 2.64 - 2.61 2.51 2.68 2.79 | 94.0 93.5 Stems 93.8 94.0 93.9 – | $3.93 \\ 3.99 \\ 4.16 \\ 3.54 \\ 3.54 \\ 3.56 \\ 3.86 \\ 3.78 \\ 3.71 \\ 3.88 \\ 4.17 \\ $ | 3.29 3.18 3.24 3.08 3.08 3.33 3.11 3.24 3.18 3.27 | 3.42 3.54 2.93 3.09 3.22 3.24 3.09 3.27 3.49 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U-2 DFL-SE CRN-MS GCRN DCCRN TFSNN | AN N net | Wavefe Magni Magni Wavefe Wavefe Magni RI com RI com Wavefe Propos | orm tude tude orm Non-G orm orm tude ponent orm orm ed Cyc | AN 1 s s leGA | 2.64 2.86 2.92 2.36 based Sys 2.64 - 2.61 2.51 2.68 2.79 N-based | 94.0 93.5 5tems 93.8 93.8 94.0 93.9 – approaches | 3.93 3.99 4.16 3.54 3.56 3.86 3.78 3.71 3.88 4.17 | 3.29 3.18 3.24 3.08 3.33 3.11 3.24 3.18 3.27 | 3.42 3.54 2.93 3.09 3.22 3.24 3.09 3.27 3.49 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U- DFL-SE CRN-MS GCRN DCCRN TFSNN MCGAN | AN N net E | Wavefe Magni Magni Wavefe Wavefe Magni RI com RI com Wavefe Propos | orm tude tude orm Non-G orm orm tude ponent orm orm sed Cyc tude | AN s s leGA | 2.64 2.86 2.92 2.36 based Sys 2.64 - 2.61 2.51 2.68 2.79 AN-based 2.74 | 94.0 93.5 stems - 93.8 94.0 93.9 - approaches 93.6 | 3.93 3.99 4.16 3.54 3.56 3.86 3.78 3.71 3.88 4.17 3.88 4.17 | 3.29 3.18 3.24 3.08 3.33 3.11 3.24 3.18 3.27 3.25 3.25 | 3.42 3.54 2.93 3.09 3.22 3.24 3.09 3.27 3.49 3.29 3.29 | | |
| CP-GAN MetricGA CRGAN SASEGA Wave-U-2 DFL-SE CRN-MS GCRN DCCRN TFSNN TFSNN | AN N net | Wavefe Magni Magni Wavefe Wavefe Magni RI com RI com Wavefe Propos Magni RI com | orm tude tude orm Non-G orm orm tude ponent orm ed Cyc tude ponent | AN 1 s s leGA | 2.64 2.86 2.92 2.36 based Sys 2.64 - 2.61 2.51 2.68 2.79 N-based 2.74 2.60 | 94.0 93.5 Stems - 93.8 94.0 93.9 - approaches 93.6 92.8 | 3.93 3.99 4.16 3.54 3.54 3.56 3.86 3.78 3.71 3.88 4.17 3.88 4.17 3.96 3.96 3.82 | 3.29 3.18 3.24 3.08 3.08 3.33 3.11 3.24 3.18 3.27 3.25 3.12 | 3.42 3.54 2.93 3.09 3.22 3.24 3.09 3.27 3.49 3.27 3.49 | | |

Conclusions

• This paper proposes a novel Cycle-in-Cycle GAN dubbed CinCGAN to jointly recover the spectral magnitude and phase information of clean speech for non-parallel speech enhancement. • The proposed system surpasses previous state-of-the-art non-parallel GAN based speech enhancement systems, indicating the superiority of the cycle-in-cycle paradigm under mismatched noisy-clean pairs. • When experiments are conducted on standard parallel data, the proposed approach also demonstrates its effectiveness in

improving speech quality and reducing speech distortion.