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SDNet: Noise-Robust Bandwidth Extension under Flexible Sampling Rates

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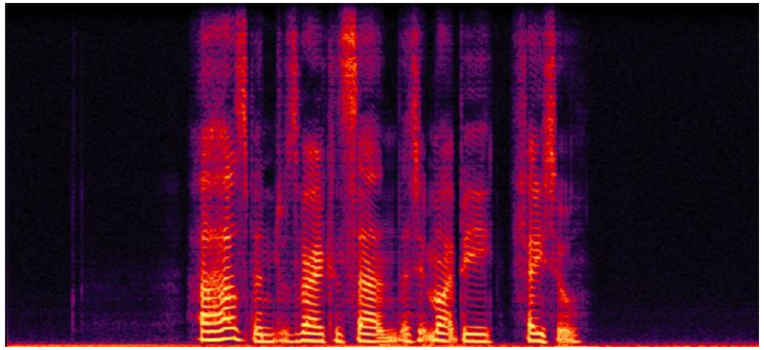
Introduction

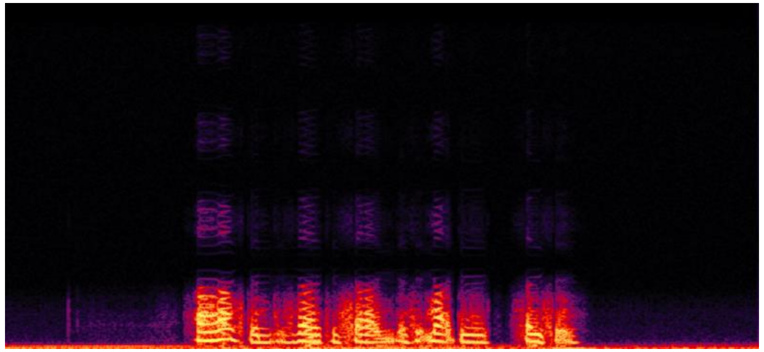
- What is Bandwidth Extension (also named as Audio Super-Resolution)?

Recovering high-resolution (HR) signals from low-resolution (LR) counterparts.

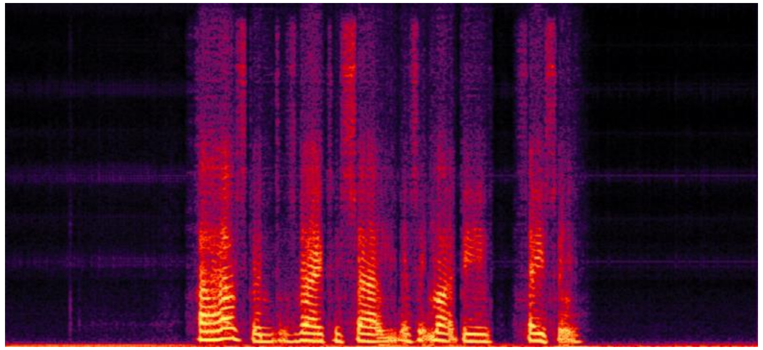
- Applications: wireless communication, speech recognition, text-to-speech.



Original



Low-Resolution



Super-Resolution

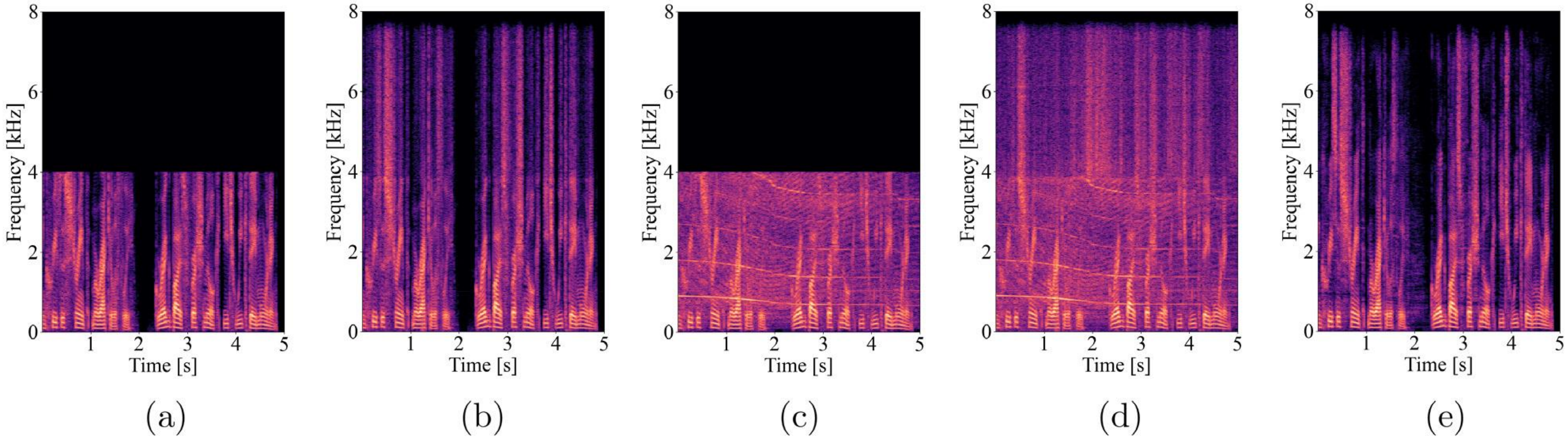
- Problem: Current models struggle with noisy environments and flexible sampling rates.

- Goal: Jointly handle noise reduction and bandwidth extension and support multiple sampling rates with a single model.

Challenges in BWE

- Ineffectiveness in noisy environments

Noise interference biases high-frequency predictions.



Challenges in BWE

- Limited flexibility: Fixed sampling rates in most models.

		SingleSpeaker			MultiSpeaker			Piano		
Ratio	Obj.	Spline	DNN	Ours	Spline	DNN	Ours	Spline	DNN	Ours
$r = 2$	SNR	20.3	20.1	21.1	19.7	19.9	20.7	29.4	29.3	30.1
	LSD	4.5	3,7	3.2	4.4	3.6	3.1	3.5	3.4	3.4
$r = 4$	SNR	14.8	15.9	17.1	13.0	14.9	16.1	22.2	23.0	23.5
	LSD	8.2	4.9	3.6	8.0	5.8	3.5	5.8	5.2	3.6
$r = 6$	SNR	10.4	n/a	14.4	9.1	n/a	10.0	15.4	n/a	16.1
	LSD	10.3	n/a	3.4	10.1	n/a	3.7	7.3	n/a	4.4

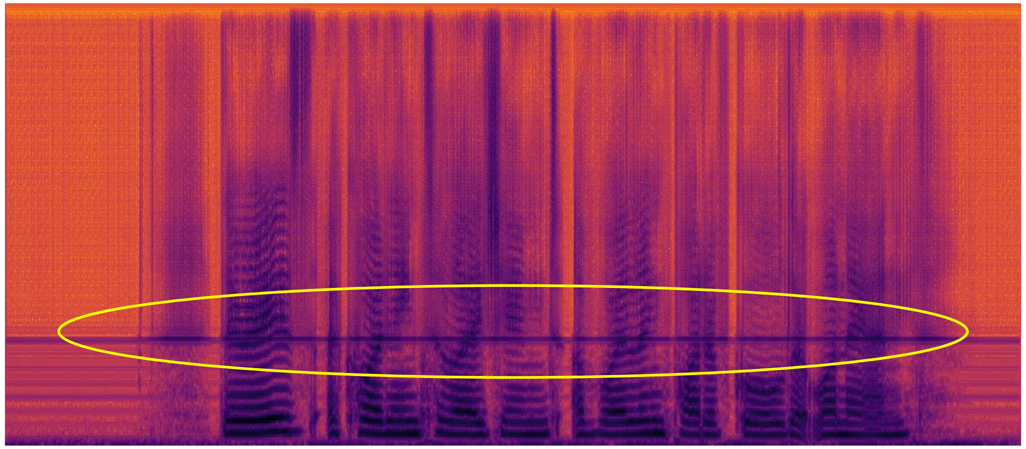
Table 2: Accuracy evaluation of audio-super resolution methods (in dB) on each of the three super-resolution tasks at upscaling ratios $r = 2, 4, 6$.

Table 1: L, V and M denote LSD, ViSQOL and MUSHRA respectively. MUSHRA score is specified with a ± Confidence Interval of 0.95.

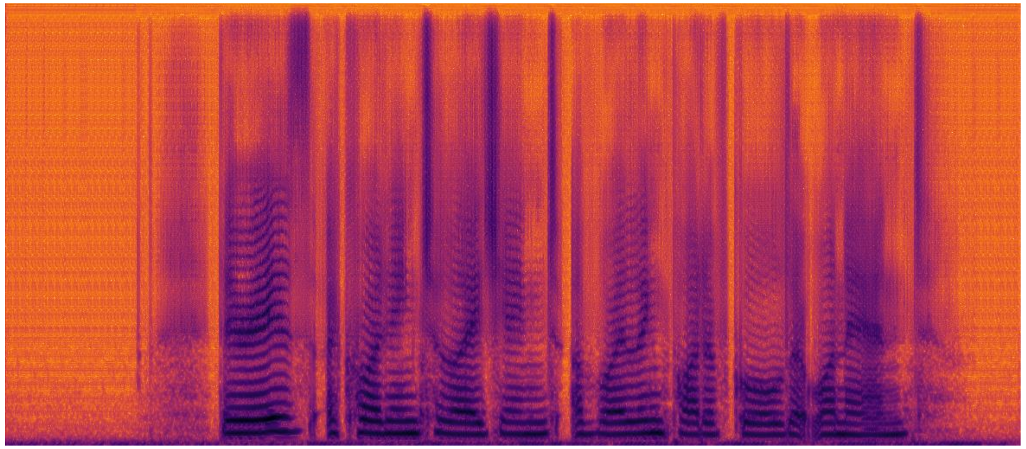
	8-16			8-24			4-16			11-44		
	L↓	V↑	M↑	L↓	V↑	M↑	L↓	V↑	M↑	L↓	V↑	M↑
Reference	-	-	96.25±1.5	-	-	97.16±1.4	-	-	96.18±1.5	-	-	95.30±2.5
Anchor	-	-	54.65±4.3	-	-	56.21±4.4	-	-	41.14±3.8	-	-	46.55±7.4
Sinc	2.32	3.41	60.13±4.7	2.96	3.41	59.49±4.8	3.59	2.27	43.03±3.9	3.91	1.97	47.61±8.0
TFiLM [4]	1.27	3.18	58.53±4.0	-	-	-	1.77	2.25	41.91±4.0	-	-	-
SEANet [5]	0.79	4.08	91.23±2.9	0.91	4.06	94.16±2.2	0.99	3.16	89.40±3.2	1.13	2.88	80.52±7.0
BEHMGAN [17]	-	-	-	-	-	-	-	-	-	1.80	2.01	46.27±8.3
Ours ($^{256}/_{512}$)	0.84	4.02	90.58±2.3	0.99	4.03	**96.40**±1.9	1.04	3.04	86.14±3.4	1.16	2.88	81.21±6.4
Ours ($^{128}/_{512}$)	0.80	4.11	92.63±2.4	0.91	4.12	95.41±2.0	0.99	3.15	**92.05**±2.7	1.16	**2.89**	81.67±6.8
Ours ($^{64}/_{512}$)	**0.77**	**4.16**	**94.64**±1.6	**0.90**	**4.17**	94.45±2.1	**0.94**	**3.28**	90.61±3.1	**1.12**	2.88	**84.18**±5.6

Challenges in BWE

- Significant artifacts



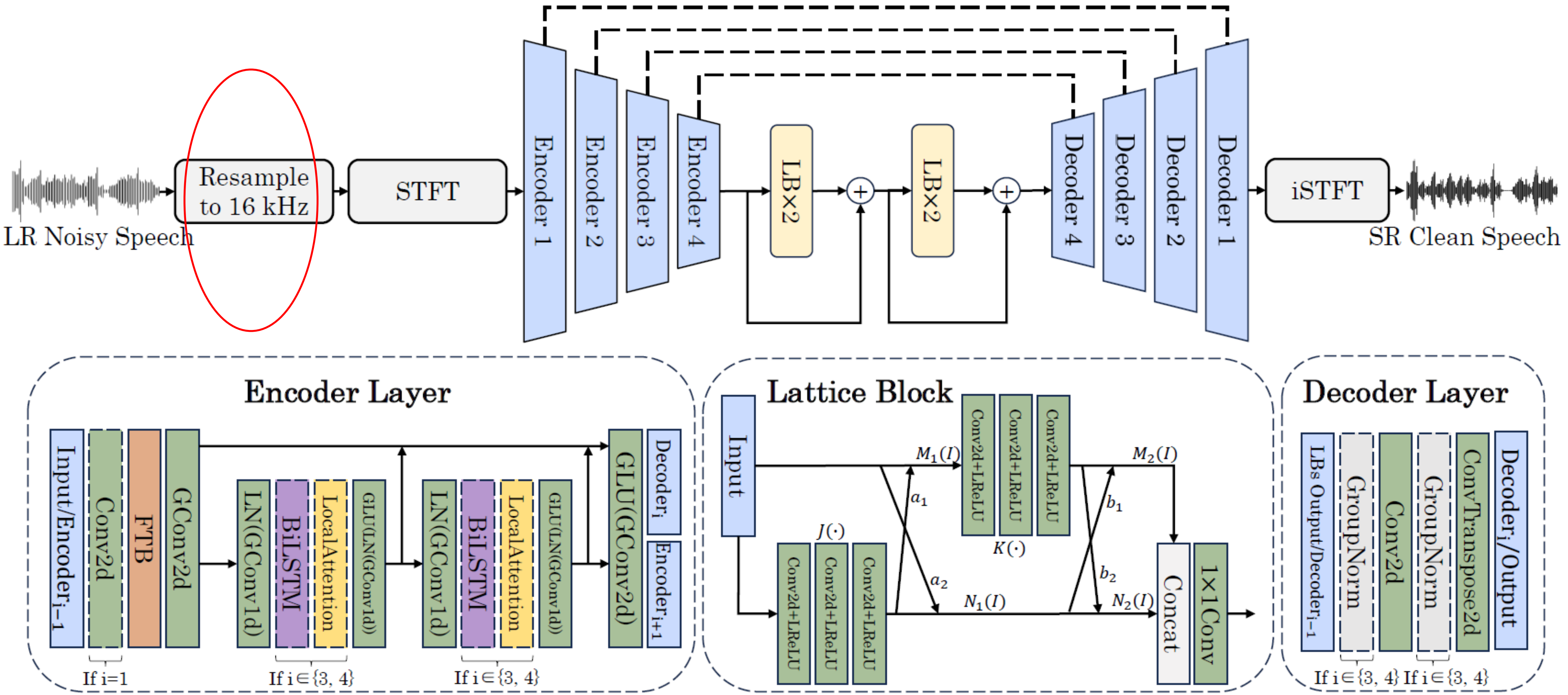
Super-Resolution Speech



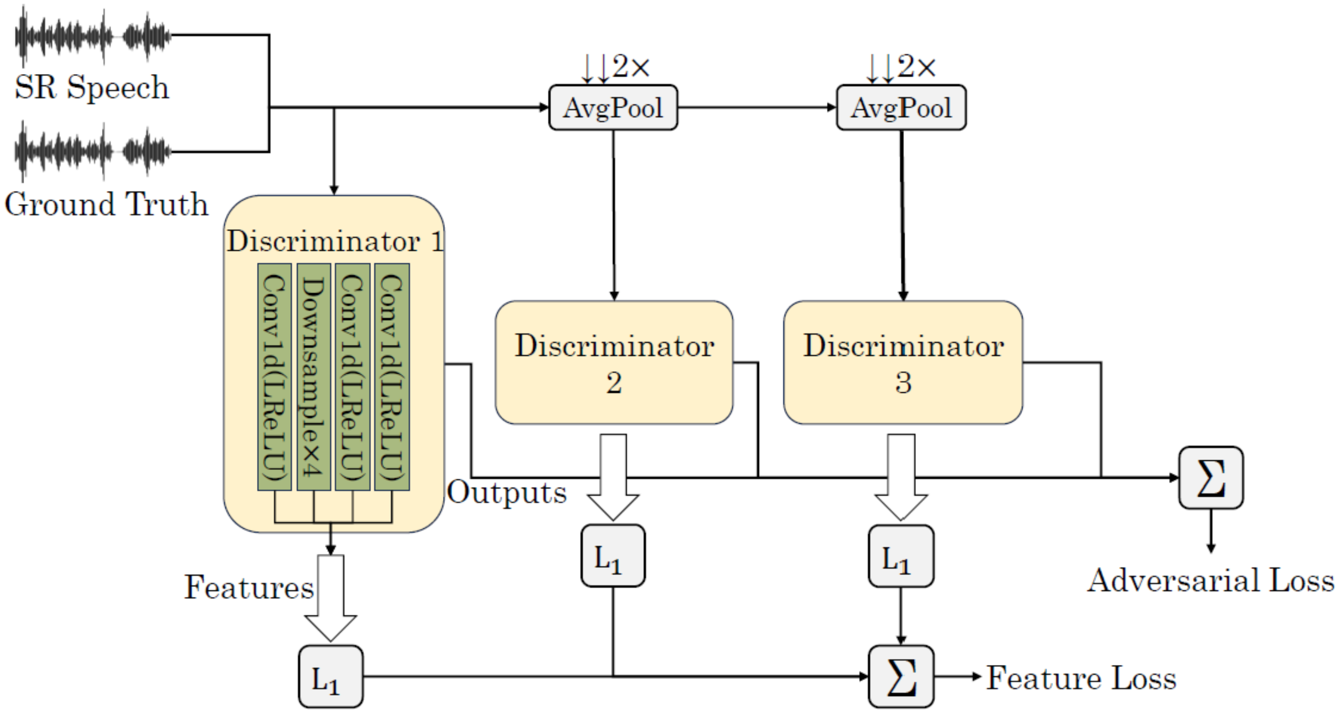
Ground Truth

- Lack of joint optimization for noise suppression and super-resolution. There are relatively few studies on noise-robust BWE compared to noise-free BWE.

Proposed Solution: SDNet



Proposed Solution: SDNet



Total Loss:

$$\mathcal{L} = \mathcal{L}_{MSTFT} + \mathcal{L}_G^{adv} + \lambda_f \mathcal{L}_f \qquad \lambda_f = 100$$

$$\mathcal{L}_{MSTFT} = E_{(x,y)\sim p_{data}} \left[\sum_{m=1}^{3} \left(\frac{||s(y,\theta_m) - s(x,\theta_m)||_F}{||s(y,\theta_m)||_F} + \frac{1}{N} ||log \frac{s(y,\theta_m)}{s(x,\theta_m)}|| \right) \right]$$

$||\cdot||_F$ and $||\cdot||_1$ are Frobenius and ℓ1-norms, N is the number of elements in the magnitude.

FFT bins ∈ {512, 1024, 2048} and hop length ∈ {50, 120, 240}. The window lengths are {240, 600, 1200}.

$$\mathcal{L}_G^{adv} = E_{x\sim p_{data}} \left[\frac{1}{K} \sum_k max(0, 1 - D_k(G(x))) \right],$$

$$\mathcal{L}_f = E_{(x,y)\sim p_{data}} \left[\frac{1}{KL} \sum_{k,l} ||D_k^l(y) - D_k^l(G(x))||_1 \right],$$

Where *k* is the number of discriminators, *l* is the number of layer in one discriminator.

Proposed Solution: SDNet

Training Data Augmentation:

Data: $\boldsymbol{y} \in \mathbb{Y}$
Result: The high-quality speech $\boldsymbol{y}$ and its downsampled version $\boldsymbol{x}$
$\boldsymbol{x} = \boldsymbol{s}$;
type $=$ random type (Chebyshev, Elliptic, Butterworth, Boxcar);
$f_{cut} \sim U(C_{low}, C_{high})$;
$order \sim U(O_{low}, O_{high})$;
$\boldsymbol{x} = \boldsymbol{x} * Filter(type, f_{cut}, order)$;
if resample, **then**
$\boldsymbol{x} = Resample(Resample(\boldsymbol{x}, 16000, f_{cut} \times 2), f_{cut} \times 2, 16000)$;
end if

We use a filter with random parameters when doing downsampling, the types include *Chebyshev, Elliptic, Butterworth* and *Boxcar*, the order is a random integer from 2 to 10, the cutoff frequency is an integer from 2000 to 8000 Hz. SNR: [-5, 20] dB.

Datasets(noise & speech):
DNS Challenge dataset, Valentini-Botinhao dataset.

Handle uncertain low sampling rate inputs and artifacts.

Experiment Results

TABLE I

TEST RESULTS OF NOISE-ROBUST BWE MODELS ON VALENTINI-BOTINHAO NOISY TEST SET DOWNSAMPLED TO 8 KHZ.

Method	**PESQ-WB↑**	**STOI (%)↑**	**CSIG↑**	**CBAK↑**	**COVL↑**	**LSD↓**
UEE [15]	2.23	93	2.27	2.39	2.17	2.72
MTL-MBE [8]	2.55	94	2.64	3.21	2.46	2.29
EP-WUN [9]	2.25	92	**3.50**	2.94	2.86	1.23
AFiLM + I-DTLN [4]	2.54	90	2.63	2.87	2.18	1.54
Ours	**2.67**	**95**	3.29	**3.32**	**2.92**	**1.16**

Experiment Results

TABLE II

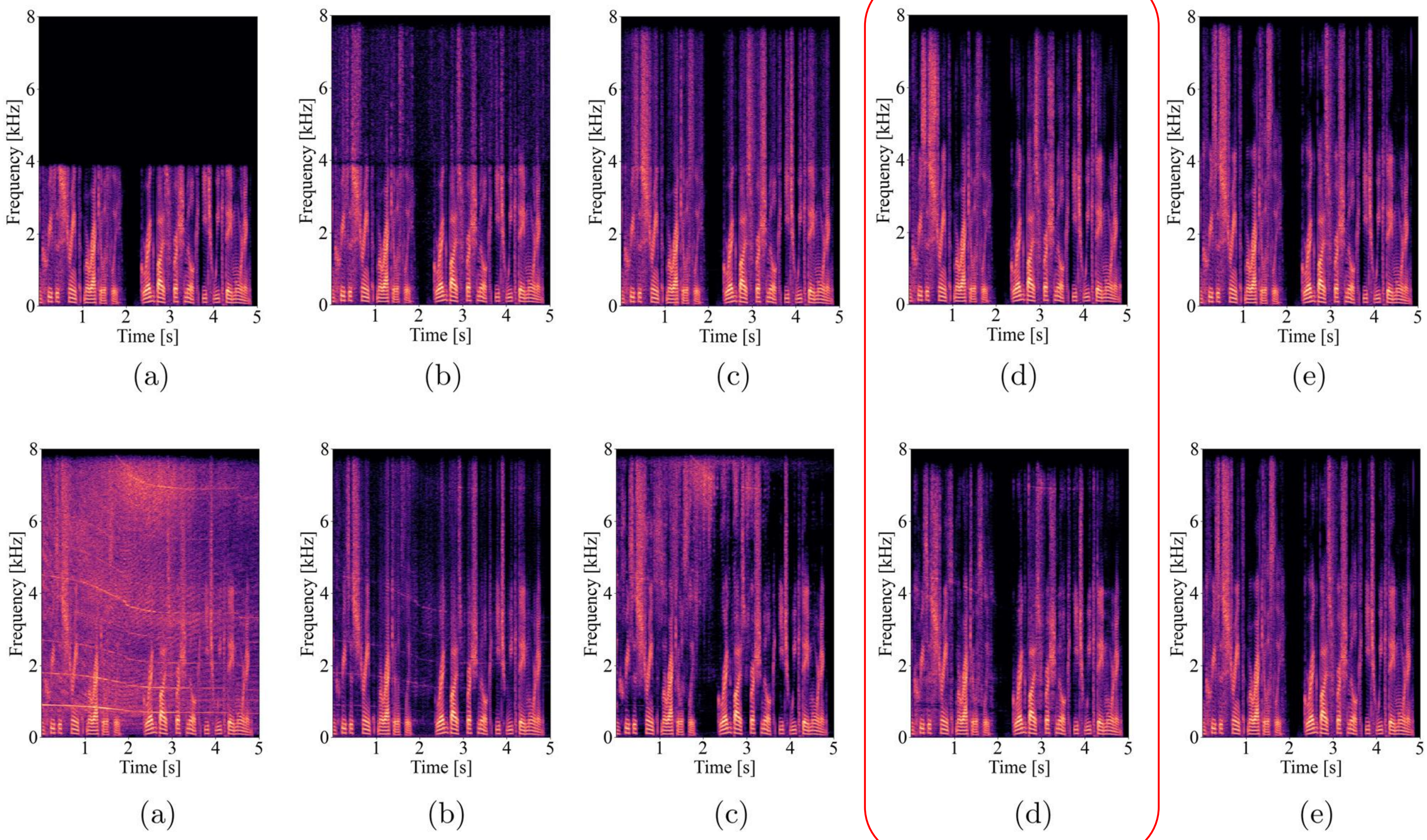
TEST RESULTS FOR DIFFERENT TASK ON DNS-CHALLENGE NO-REVERB TEST. "B" IS NOISE-FREE BWE, "D" IS DENOISE, AND "RB" IS NOISE-ROBUST BWE. "SOURCE" AND "NOISE" REPRESENT THE SAMPLING RATE OF INPUTS AND THE CASE WHETHER THE INPUTS CONTAIN NOISES.

Method	Task	Source	Noise	PESQ-NB↑	PESQ-WB	STOI(%)	CSIG	CBAK	COVL	LSD	MOS↑
WSRGlow	B	8 kHz	×	4.365	2.811	**99.4**	3.946	4.068	3.433	0.929	4.21
NU-Wave 2	B	8 kHz	×	4.353	2.646	**99.4**	3.663	2.869	3.209	1.328	4.08
AERO	B	8 kHz	×	4.369	3.295	98.5	**4.287**	4.273	3.844	0.802	4.27
Ours	B	8 kHz	×	**4.377**	**3.661**	98.6	4.103	**4.553**	**3.935**	**0.783**	**4.55**
DCCRN	D	16 kHz	✓	3.17	2.64	92.9	—	—	—	—	—
FullSubNet	D	16 kHz	✓	3.28	2.72	95.3	—	—	—	—	—
DPT-FSNet	D	16 kHz	✓	3.28	2.72	95.3	—	—	—	—	—
Ours	D	16 kHz	✓	**3.29**	**2.80**	**96.0**	—	—	—	—	—
VoiceFixer	RB	8 kHz	✓	2.535	1.679	84.0	2.532	1.914	2.043	1.323	3.83
Ours	RB	8 kHz	✓	**3.554**	**2.777**	**97.1**	**3.313**	**3.532**	**3.063**	**1.218**	**4.38**
VoiceFixer	RB	4-16 kHz	✓	2.540	1.822	84.2	2.737	1.984	2.222	1.280	3.89
Ours	RB	4-16 kHz	✓	**3.550**	**3.013**	**97.3**	**3.657**	**3.726**	**3.355**	**1.112**	**4.43**

Experiment Results

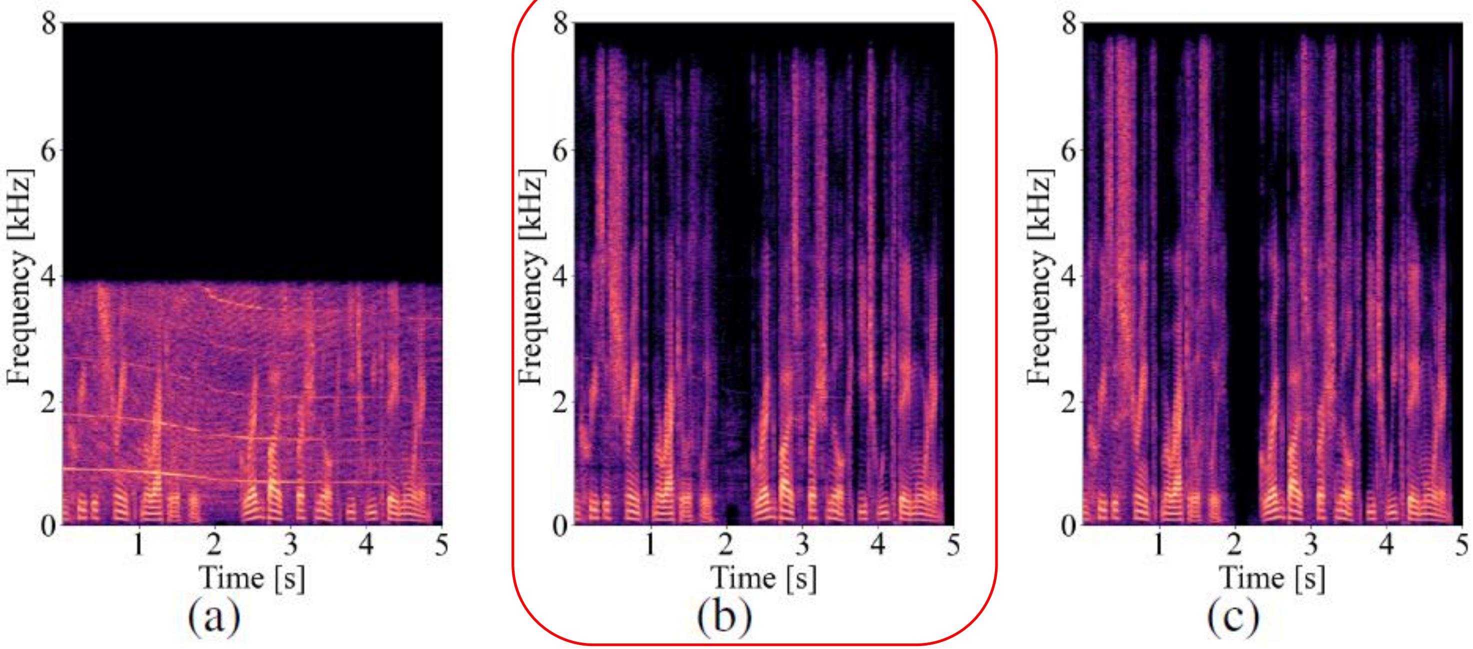
BWE:

Denoise:



Experiment Results

Noise-Robust BWE:



More samples in our demo page:

https://sdnetdemo.github.io/

Conclusions

SDNet Contributions:
- First noise-robust BWE supporting flexible sampling rates.
- Joint optimization for noise reduction and super-resolution.
- Superior performance across diverse scenarios.

Limitations:
- Challenges with higher resolution (e.g., 48 kHz).

Future Work:
- Extend to music datasets and higher resolutions.

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