RADE - Machine Learning for Speech over HF Radio

freedv.org

Supported by a grant from Amateur Radio Digital Communications

October 10, 2025

Outline

RADE Radio Auto-encoder

- Applying machine learning (ML) to send speech over HF radio
- Combines traditional DSP and modern ML to encode and decode speech
- Connect a PC running RADE to your SSB radio
- 8 kHz audio bandwidth, high quality speech
- Works at low and high SNRs, handles multipath fading

RADE Examples

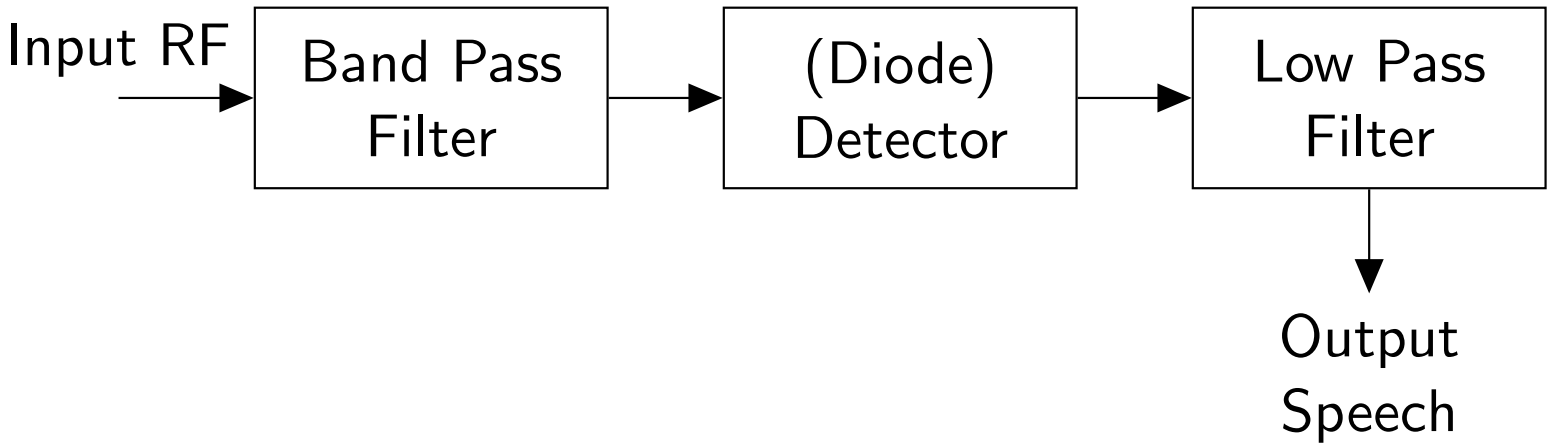
- Texas to Australia, 25W, SNR 4 dB, deep fading ▸ Link
- 2000km Australian path, low and high SNR, barber pole fading ▸ Link

RADE is an outcome of the FreeDV Project ...

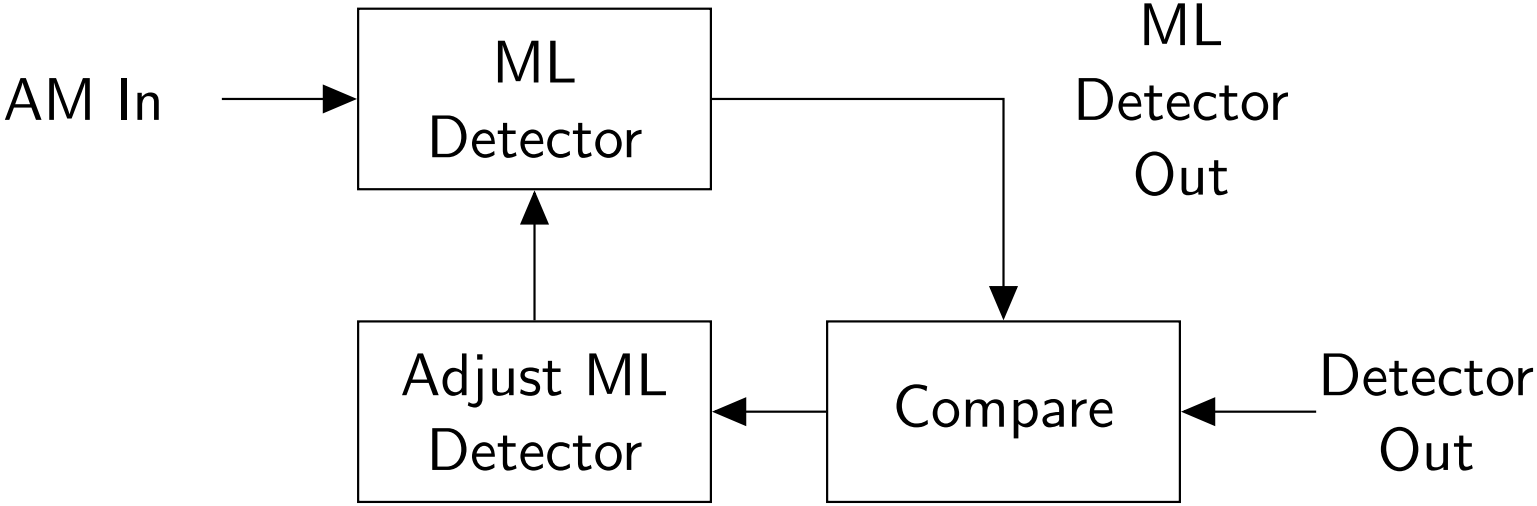
- Open source HF digital voice for amateur radio
- Since 2023, funded by an ARDC grant
- 6 person Project Leadership Team, 2 part time engineers
- Financial sponsor is the Software Freedom Conservancy
- Project Goal: a voice mode competitive with SSB at high and low SNRs

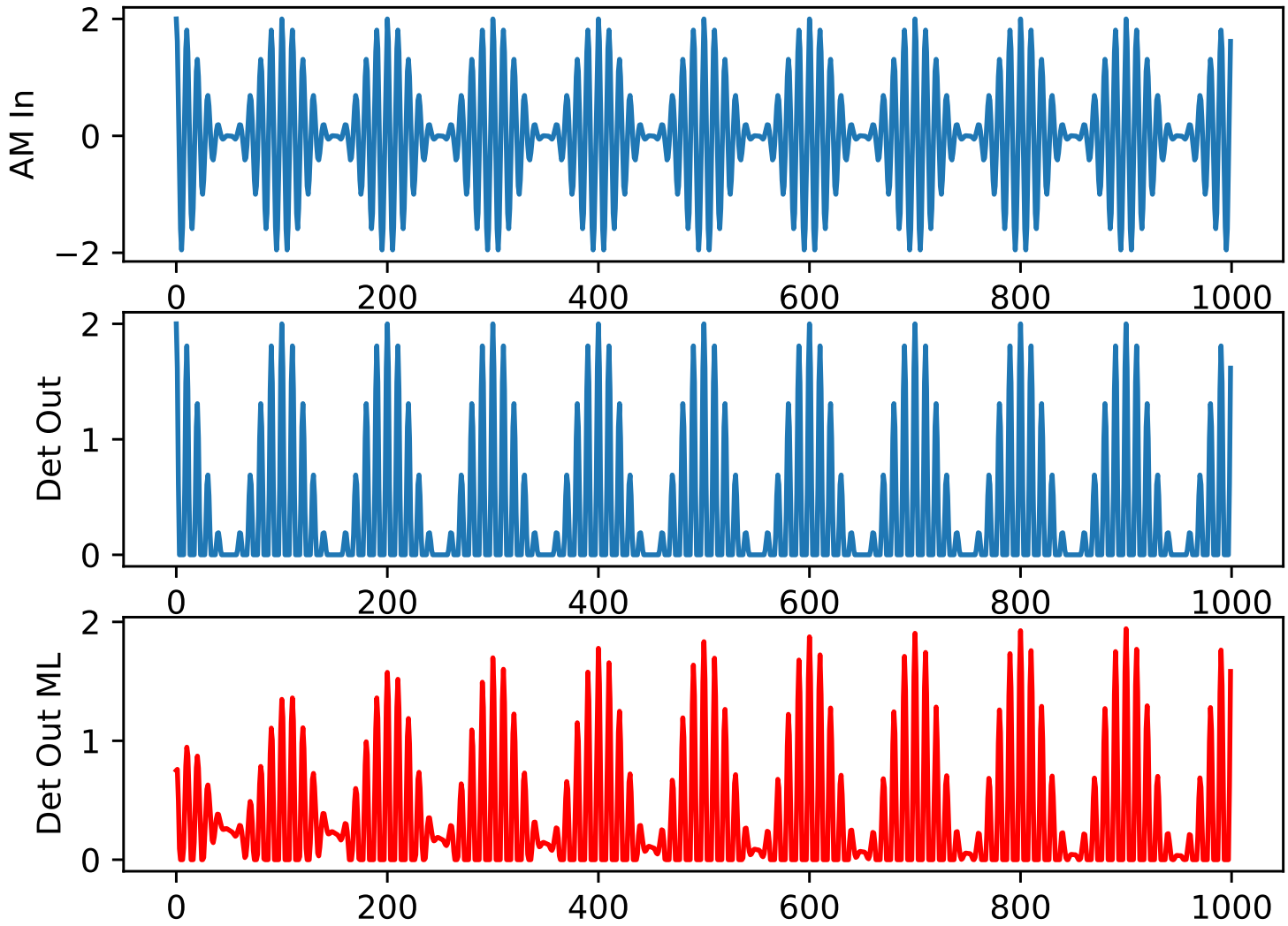
Design Versus Training

- Previously, we would design a system
- Figure out all the signal processing steps
- With ML the emphasis is on training a neural network
- Consider an AM receiver example
- Lets build the Detector using machine learning



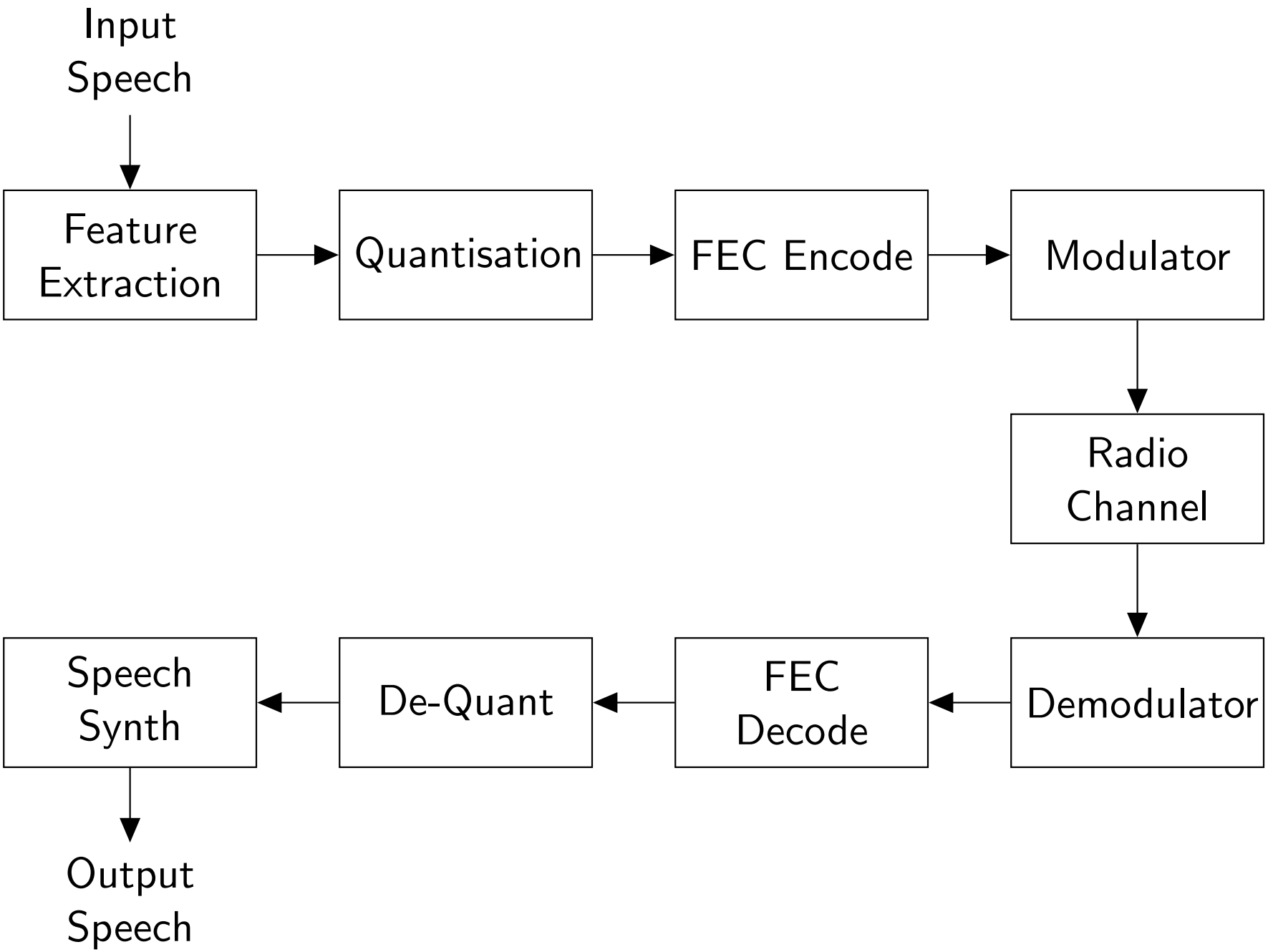
- Start with an untrained neural network
- Collect some training material
- Many examples of input and desired output
- Train the network so it matches the desired output

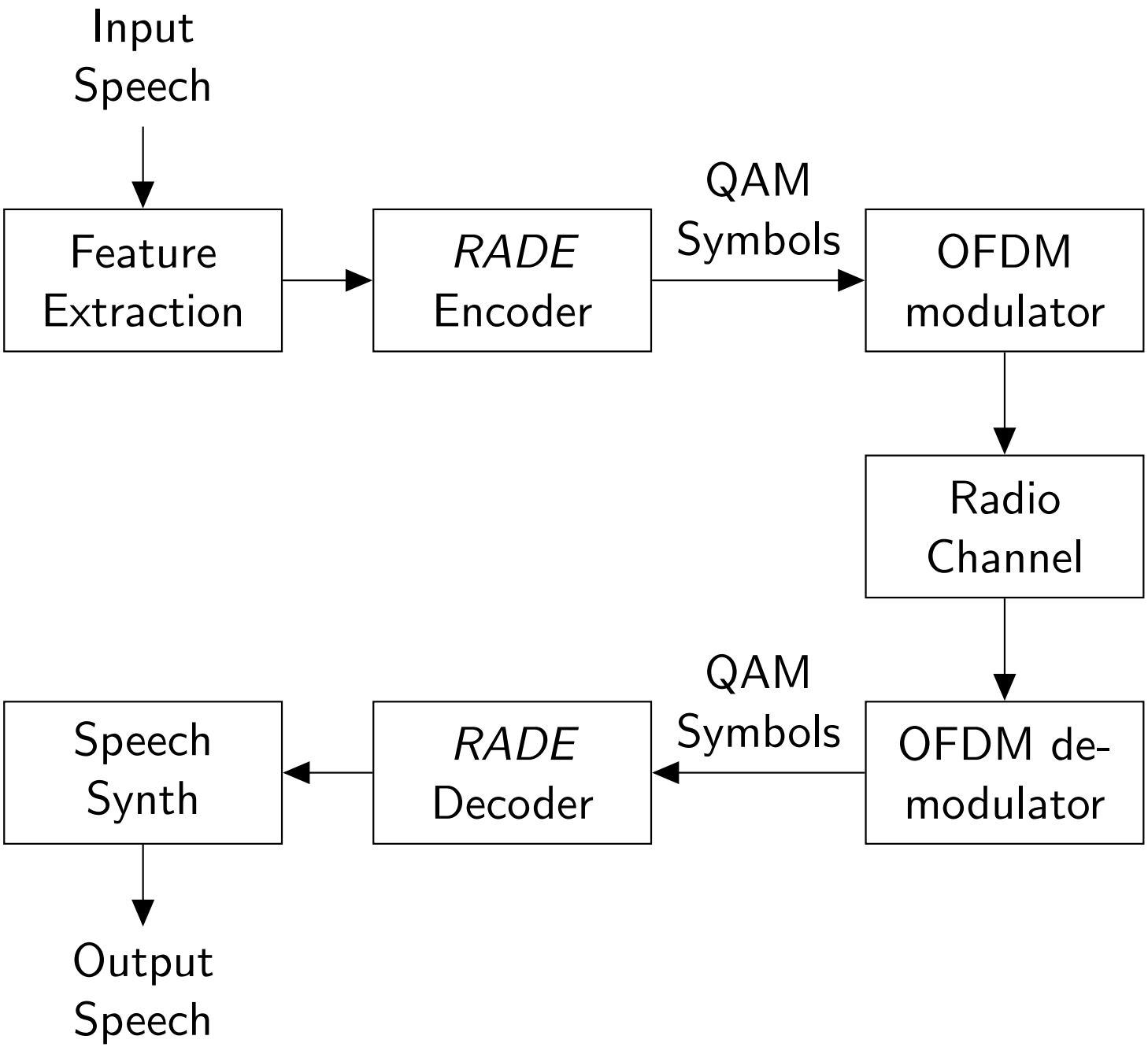



AM In
2
0
−2
0
200
400
600
800
1000
Det Out
2
1
0
0
200
400
600
800
1000
Det Out ML
2
1
0
0
200
400
600
800
1000

- Sometimes we don't know the best way to design something
- Real world problems are complex, perfect designs don't exist
- But we do have a good idea of what success looks (sounds) like
- So we just treat the system as a black box
- Show it examples of what we would like to see - and train
- ML has provided step changes in performance for many applications
- Including speech synthesis and compression

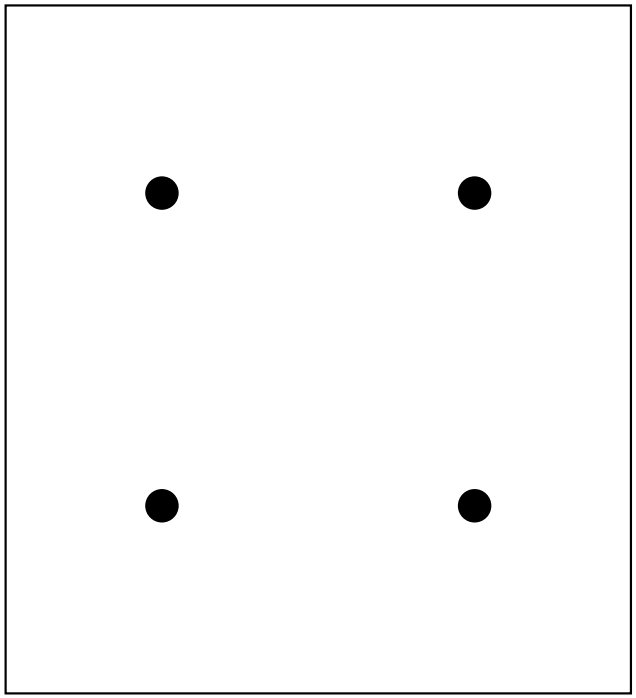
- Jean-Marc Valin (and team) - compressing speech for Internet applications
- Idea: could it could be applied to noisy signal over radio channels?
- Jean-Marc developed a quick proof of concept
- We wrapped a modem around it, developed a practical HF voice system
- Hams around the world helped crowd sourced the testing
- Mooneer Salem integrated RADE with the FreeDV GUI application


Input Speech
Feature Extraction
Quantisation
FEC Encode
Modulator
Radio Channel
Demodulator
FEC Decode
De-Quant
Speech Synth
Output Speech

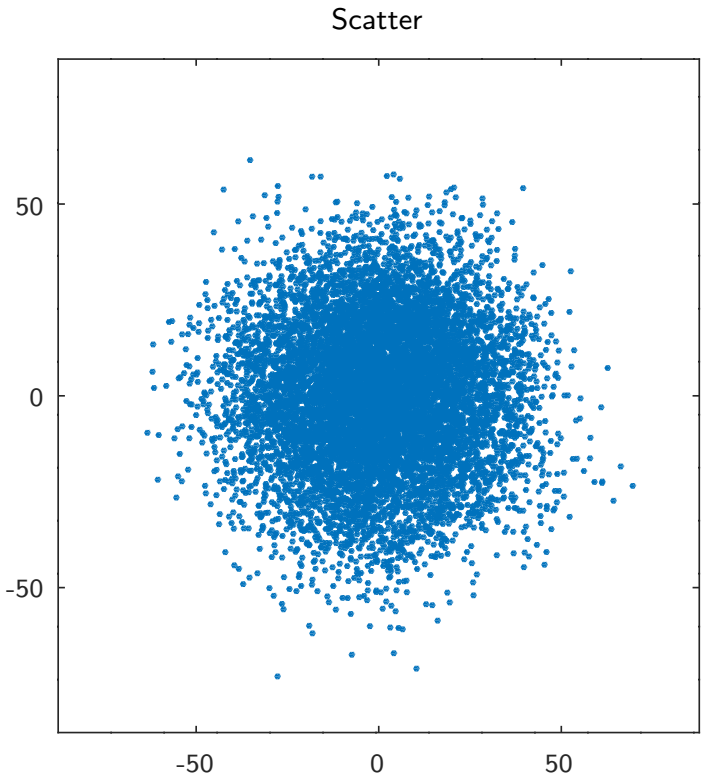

Input Speech
Feature Extraction
RADE Encoder
QAM Symbols
OFDM modulator
Radio Channel
OFDM de-modulator
QAM Symbols
RADE Decoder
Speech Synth
Output Speech

- Example of features - waterfall (aka spectrogram)
- A series of samples of the speech spectrum
- Encoder takes features and produces symbols we send over channel
- Decoder takes symbols and produces features
- Which are fed to a ML synthesiser to generate high quality speech
- Trained with 200 hours of speech, corrupted by noise and the HF channel
- Classical DSP modem wrapped around ML for synchronisation

QPSK Constellation



RADE Constellation

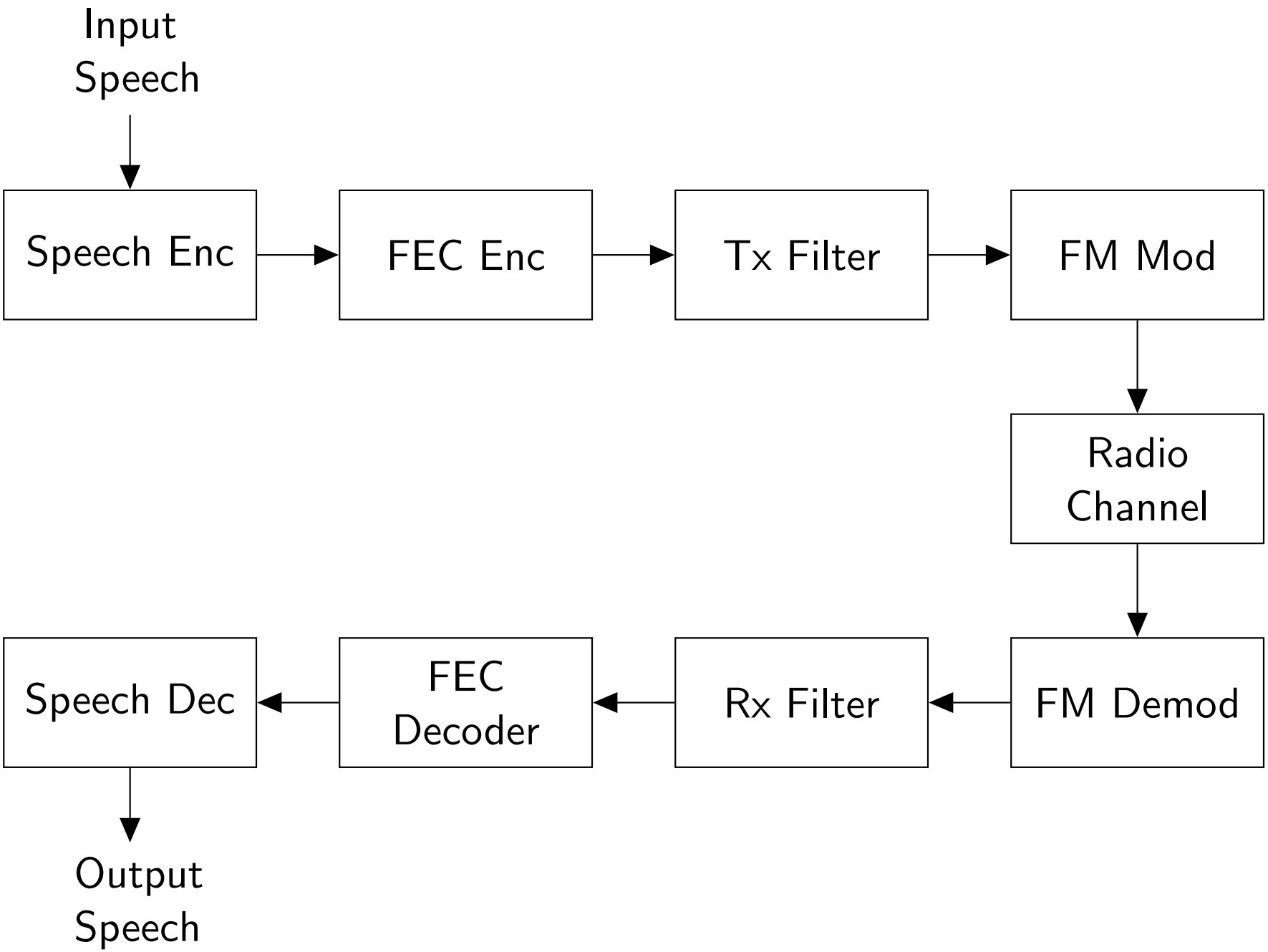


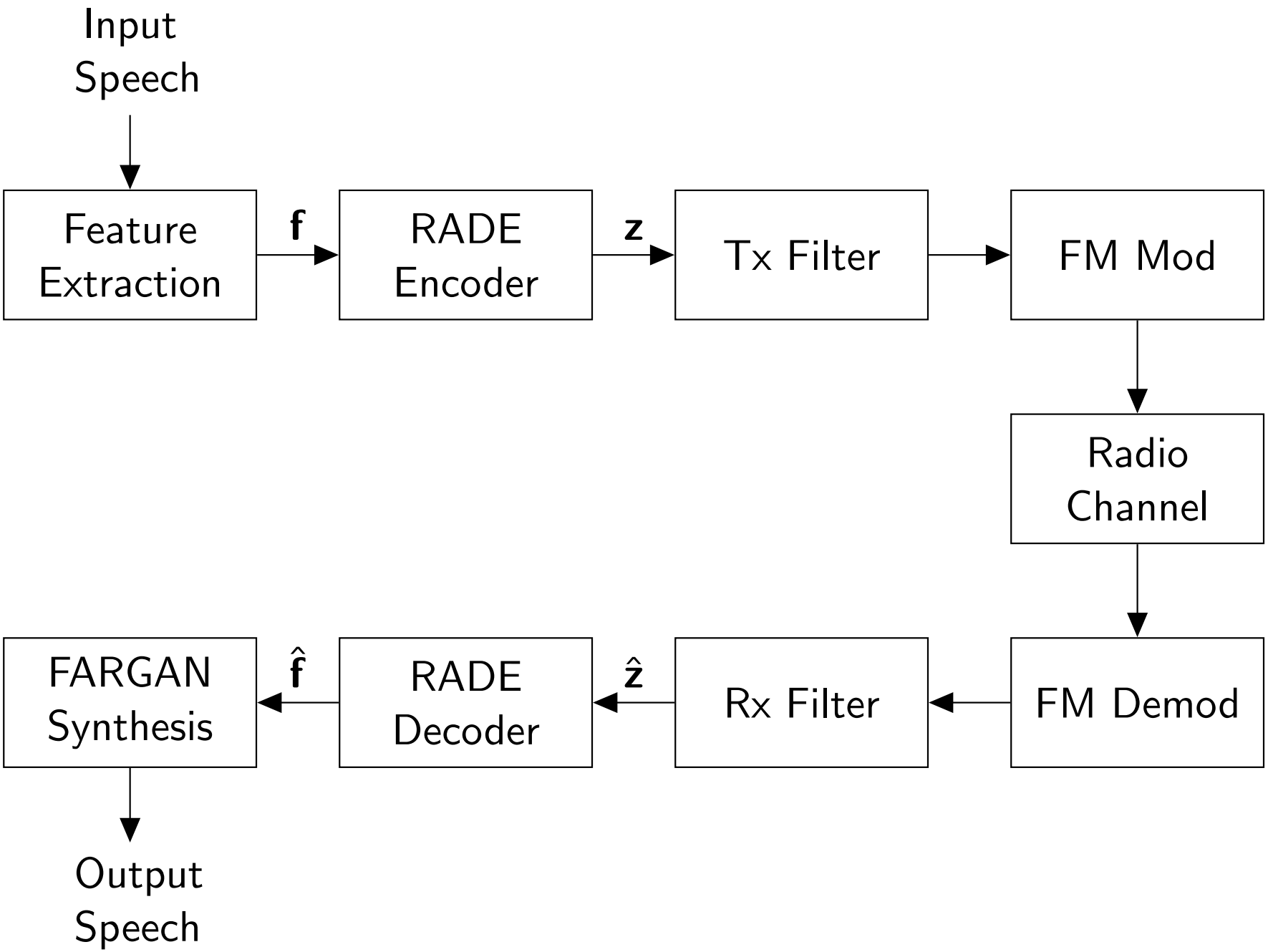
RADE BBFM

- Application of RADE for VHF/UHF
- Significant performance gains in speech quality and robustness
- High quality, 8 kHz speech, robust to fading
- Through typical analog FM "BBFM" radio architecture, as used for FM, M17, DStar etc
- We've developed the physical layer, not a complete protocol
- Like Codec 2 for M17
- Fully open source
- Our scope is HF, so this was a bonus outcome from the ARDC grant
- Downside is requires more CPU than classical vocoder (fraction of a Pi or cell phone and likely to fall)

RADE BBFM Examples

- FreeDV BBFM Page ▸ Link
- Highest quality (-100 dBm)
- Low quality (-120dBm 60 km/hr vehicle fading)


Input Speech
Speech Enc
FEC Enc
Tx Filter
FM Mod
Radio Channel
FM Demod
Rx Filter
FEC Decoder
Speech Dec
Output Speech


Input Speech
Feature Extraction
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RADE Encoder
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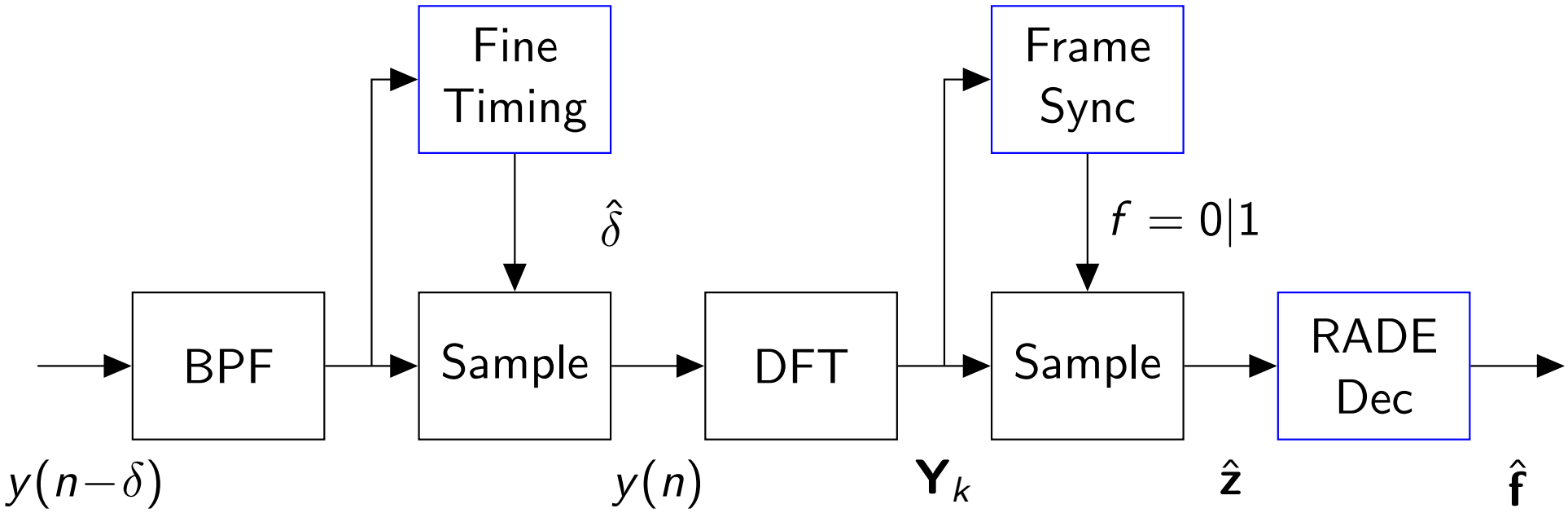
Tx Filter
FM Mod
Radio Channel
FM Demod
Rx Filter
ẑ
RADE Decoder
f̂
FARGAN Synthesis
Output Speech

RADE V2

- RADE V1 is hybrid DSP/ML design
- What if we build all components using ML?
- Status: basic OTA tests, comfirming key features.
- Building up and integrating ML signal processing blocks.
- Speech quality target $\geq$ RADE V1.
- Sensitivity target 2-3 dB better than RADE V1.

	RADE V1	RADE V2	SSB
Audio Bandwidth (Hz)	8000	8000	2400
RF Bandwidth (Hz)	1500	800	2400
99% OBW (Hz)	-	800	2400
PAPR (dB)	4.5	3	> 6
Latency (ms)	180	40	-

RADE V2 Decoder



Conclusion

- Training versus Design
- RADE - Radio Autoencoder
- RADE V1 uses ML combined with classical DSP
- High quality speech over HF at low and high SNRs
- BBFM - RADE for VHF/UHF
- RADE V2 (nearly 100% ML) in development
- Supported by a grant from Amateur Radio Digital Communications
- Developed by Hams for Hams