Feature Extraction and Selection from Vibration Measurements for Structural Health Monitoring

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Outline

- **Introduction to SHM**

- **Online Feature Extraction**
  - QAM and the Goertzel algorithm
  - Transmissibility
- **Classifier and Feature Assessment**
  - Empirically with Naive Bayes classifiers
  - Damage detection performance in large populations of randomly selected sets of features
- **Experiments and Results**

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Introduction

Structural Health Monitoring with Wireless Accelerometers

Research project (scope!)

- **Intelligent Structural Health Monitoring System**
- **Combining *wireless sensor technology* and *data analysis methods* to monitor the integrity of buildings, bridges, etc.**
- **Multidisciplinary research effort is required to study and build such a system**

Key problems

- **No (practical) sensors directly measuring damages in large civil structures**
  - Our approach: measure how vibrations propagate in the structure (an indirect method)
  - A problem: the source of vibrations (wind, traffic etc.) has unknown variability
- **Limitations of sensors**
  - Cables are too expensive and prone to failure
  - Wireless sensors have limited batteries and bandwidth

Data analysis problems

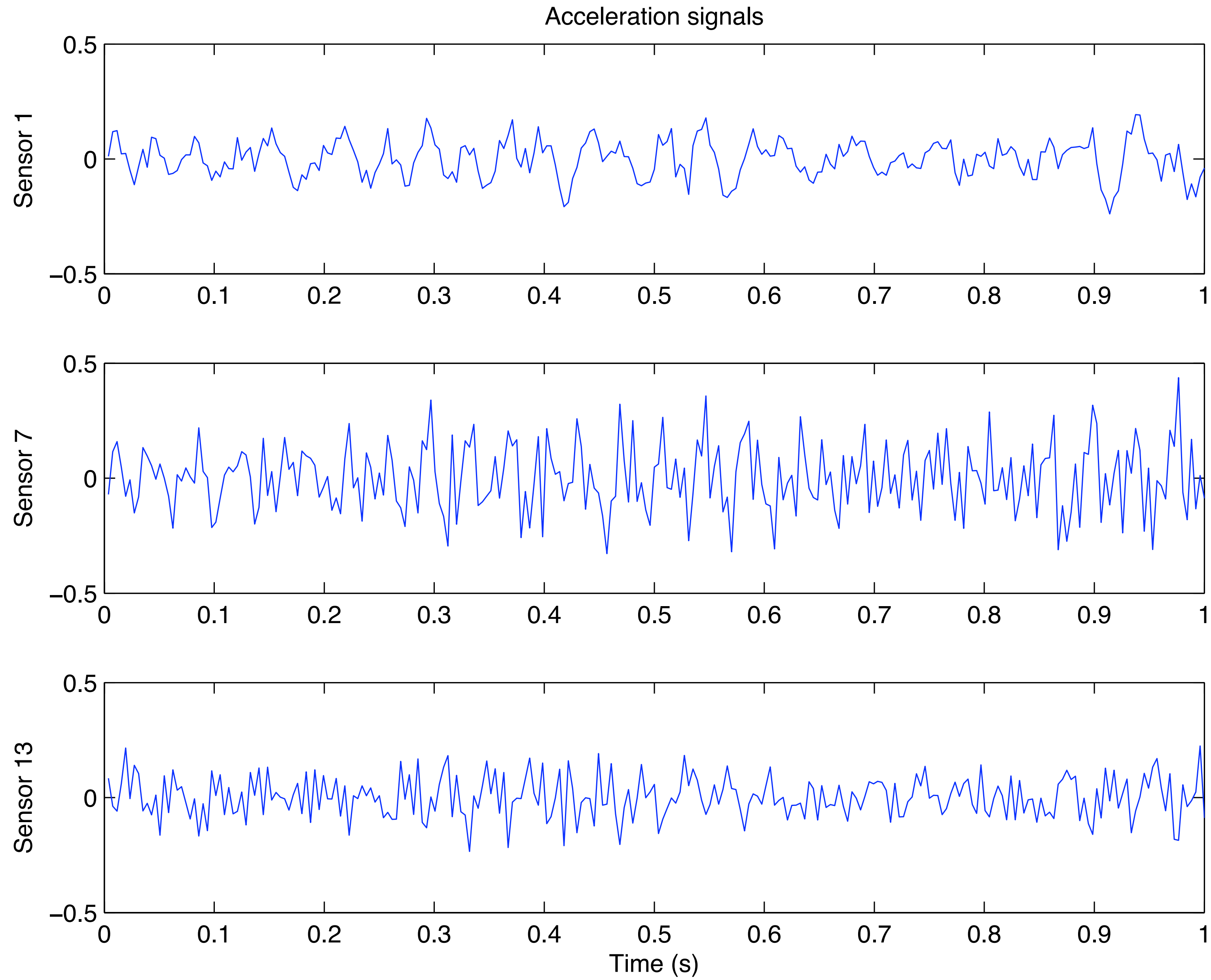
- **Can lightweight wireless sensor networks extract relevant features while discarding the irrelevant part of the data?**
  - We study the feasibility of selecting a small part of the frequency spectrum and sensors for monitoring.
- **What kind of damage detection performance can be achieved?**
  - We train classifiers with randomly selected subsets of features (feature selection/exploration).

Online Feature Extraction

Methods Suitable for Wireless Accelerometers

The acceleration data

- **Accelerometers produce concurrent streams of time domain data**

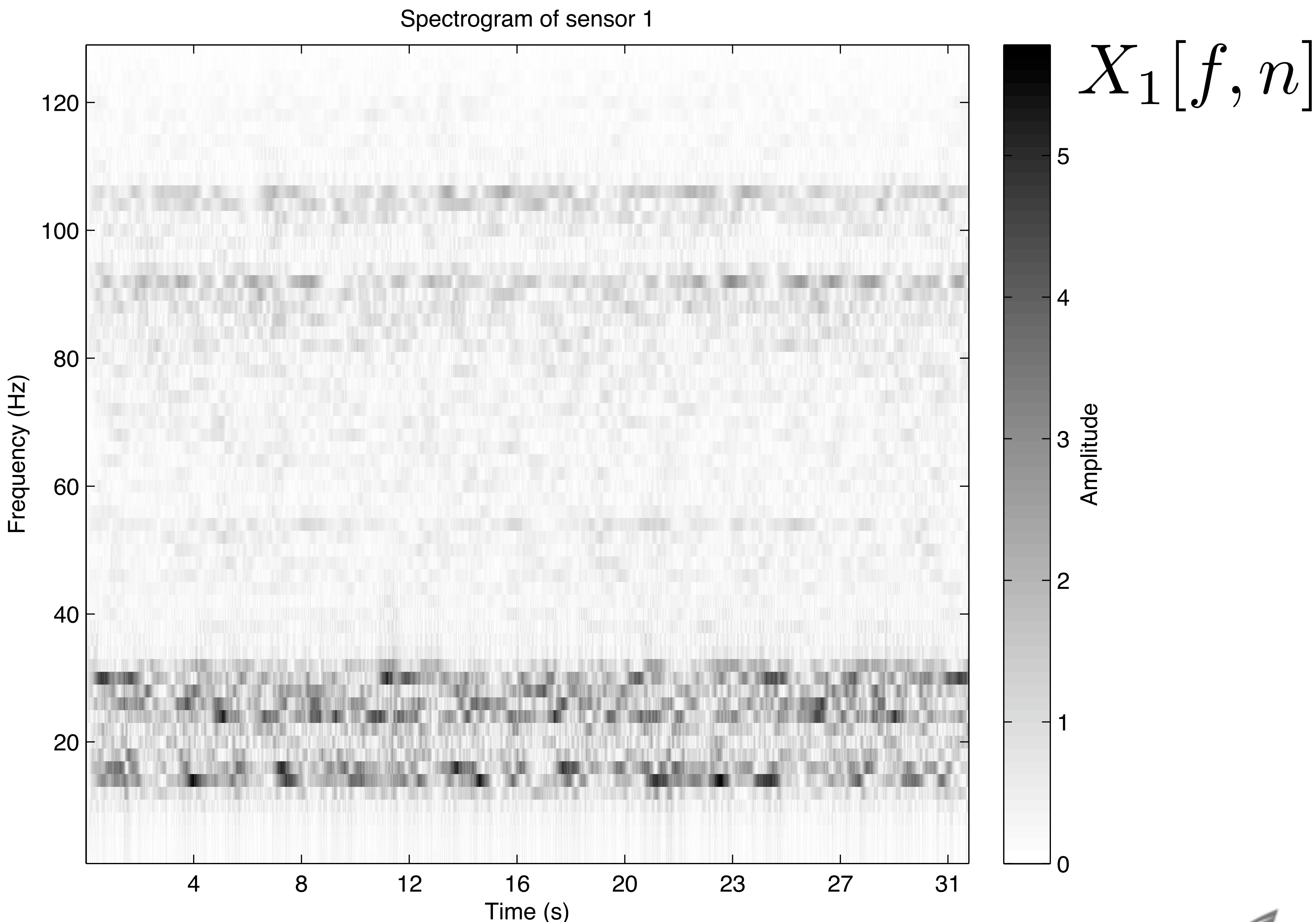


$x_1[1:256]$

$x_7[1:256]$

$x_{13}[1:256]$

The frequency domain



Domain knowledge on SHM

- **Structures vibrate mainly on their resonant frequencies (aka. normal modes)**
  - Amplitude of vibration at each location and at a given resonance frequency is called *mode shape.*
  - Damages change the properties of the structure as a medium for vibrations.
- **Our idea: monitor the amplitude of vibration only on certain frequencies at each sensor**
  - How do we select the frequencies?
  - How to monitor the medium, not the environment?

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Frequency domain analysis

- **Fast Fourier Transform (FFT) is demanding for a lightweight wireless sensor node**
  - Accurate FFT requires too many frequency bins, i.e. too much memory and energy
- **Quadrature Amplitude Modulation (QAM) considers only a narrow frequency bin**
- **Goertzel Algorithm has been used for decoding dial tones in telephone systems**

QAM receiver

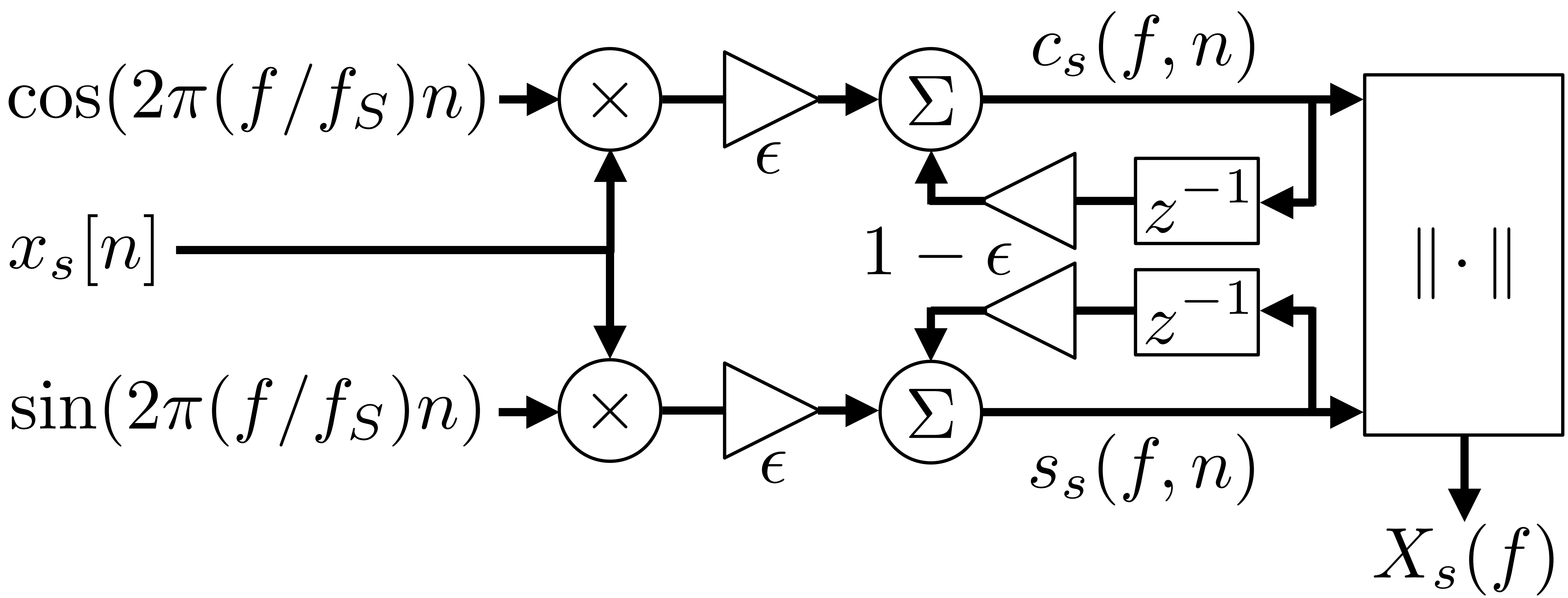
- **Amplitude monitoring: correlates the input signal $x_s[n]$ with orthogonal sine waves of the reference frequency**
  - Low-pass filtering with exponentially decaying window

$$\begin{cases} c_s(f,0) = & s_s(f,0) & = 0 \\ c_s(f,n) = & (1-\epsilon)\cdot & c_s(f,n-1)+ \\ & \epsilon\cdot & x_s[n]\cdot\cos(2\pi(f/f_s)n) \\ s_s(f,n) = & (1-\epsilon)\cdot & s_s(f,n-1)+ \\ & \epsilon\cdot & x_s[n]\cdot\sin(2\pi(f/f_s)n) \end{cases}$$

$$X_s(f) = \sqrt{c_s(f,N)^2 + s_s(f,N)^2}$$

QAM receiver

- **Needs to generate sine and cosine signals**
- **Provides also phase information (if needed)**



Goertzel Algorithm

- **Monitors a single frequency bin $k \approx N \cdot f / f_S$ with minimal computational requirements**
- **Does not provide phase information**
- **The algorithm:**

$$\begin{cases} c = & 2\cos(2\pi k/N) \\ v_k[-1] = & v_k[0] = 0 \\ v_k[n] = & x_s[n] + c \cdot v_k[n-1] - v_k[n-2] \end{cases}$$

$$|X[k]|^2 = v_k^2[N] + v_k^2[N-1] - c \cdot v_k[N] \cdot v_k[N-1]$$

Transmissibility

- **We want to monitor the structure – not some external forces of the environment**
- **Transmissibility: ratio of the vibration amplitudes at two sensor locations**
  - How vibration propagates from one sensor to the other
  - Invariant to the actual amplitude of vibration
  - Related also to *mode shapes*: amplitude profiles of standing waves across the structure

$$T(s_1, s_2, f) = X_{s_1}(f)/X_{s_2}(f)$$

Classifier and Feature Assessment

How well damages can be detected?

Classifier

- **We used Naive Bayes classifier (”off-line”)**
  - Assumes conditional independence between observed features given the class label
  - Simple model to begin with and efficient to compute
  - Ability to cope with missing data (in future)
  - Classes: the condition of the structure (”no damage”, damage 1, damage 2, ...)
  - Observed features: set of transmissibilities on certain *frequencies* and between certain *pairs of sensors*

$$P(T_1, \ldots, T_D, C) = P(C) \prod_d P(T_d | C)$$

Classifier

- **Gaussian class distributions** $P(T_d|C)$
  - Maximum Likelihood (ML) estimates of the model parameters computed from a set of training data
- **Damage detected if the log. posterior probability of the ”no damage” class is lower than a given threshold**

$$\log P(C = c|T_1 \ldots T_D) \propto$$

$$\log P(C = c) + \sum_{d=1}^{D} \left(-\log \sigma_{c,d} - \frac{(T_d - \mu_{c,d})^2}{2\sigma_{c,d}^2} \right)$$

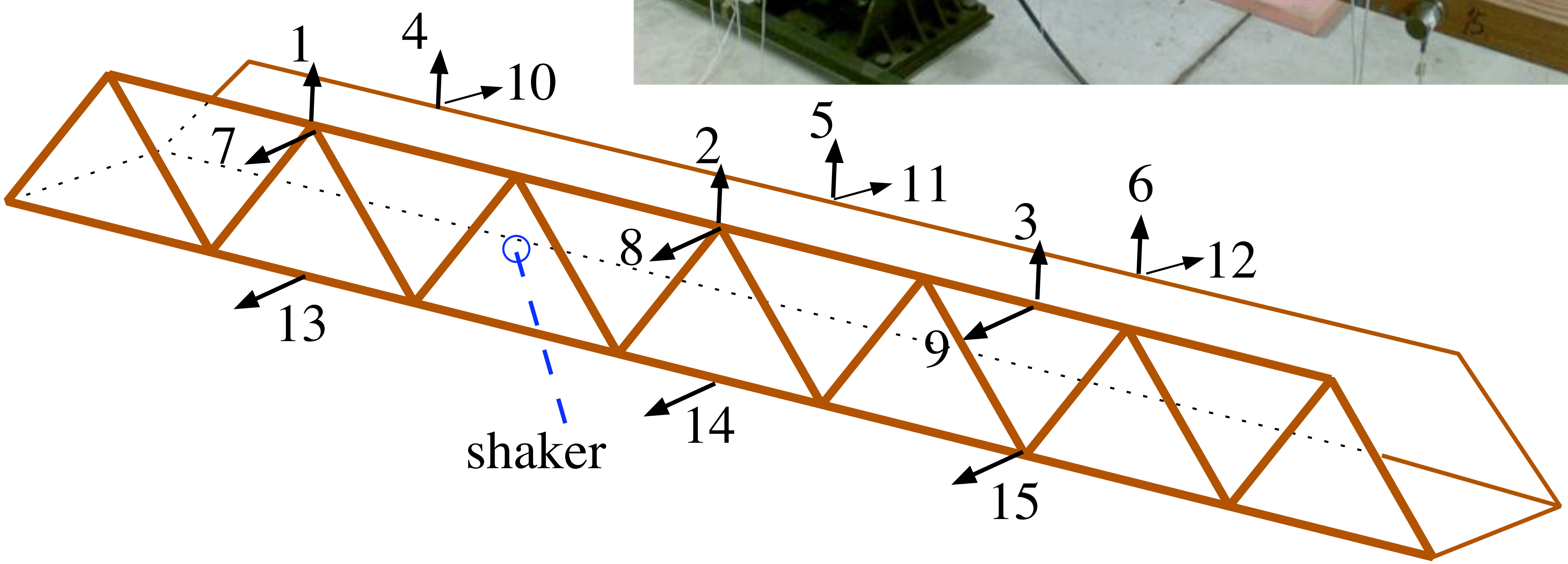
Feature selection

- **The big question: can we discard most of the data and still detect damages?**
  - Some of the frequencies and sensor pairs may contain useless noise (to our simple model at least).
  - We don’t have any additional information to guide our selection process.
- **Our empirical approach:**
  - Train a lot of classifiers on random feature sets
  - Analyse how well they detect damages in the validation data set

Experiments and Results

How did it perform on a wooden model bridge?

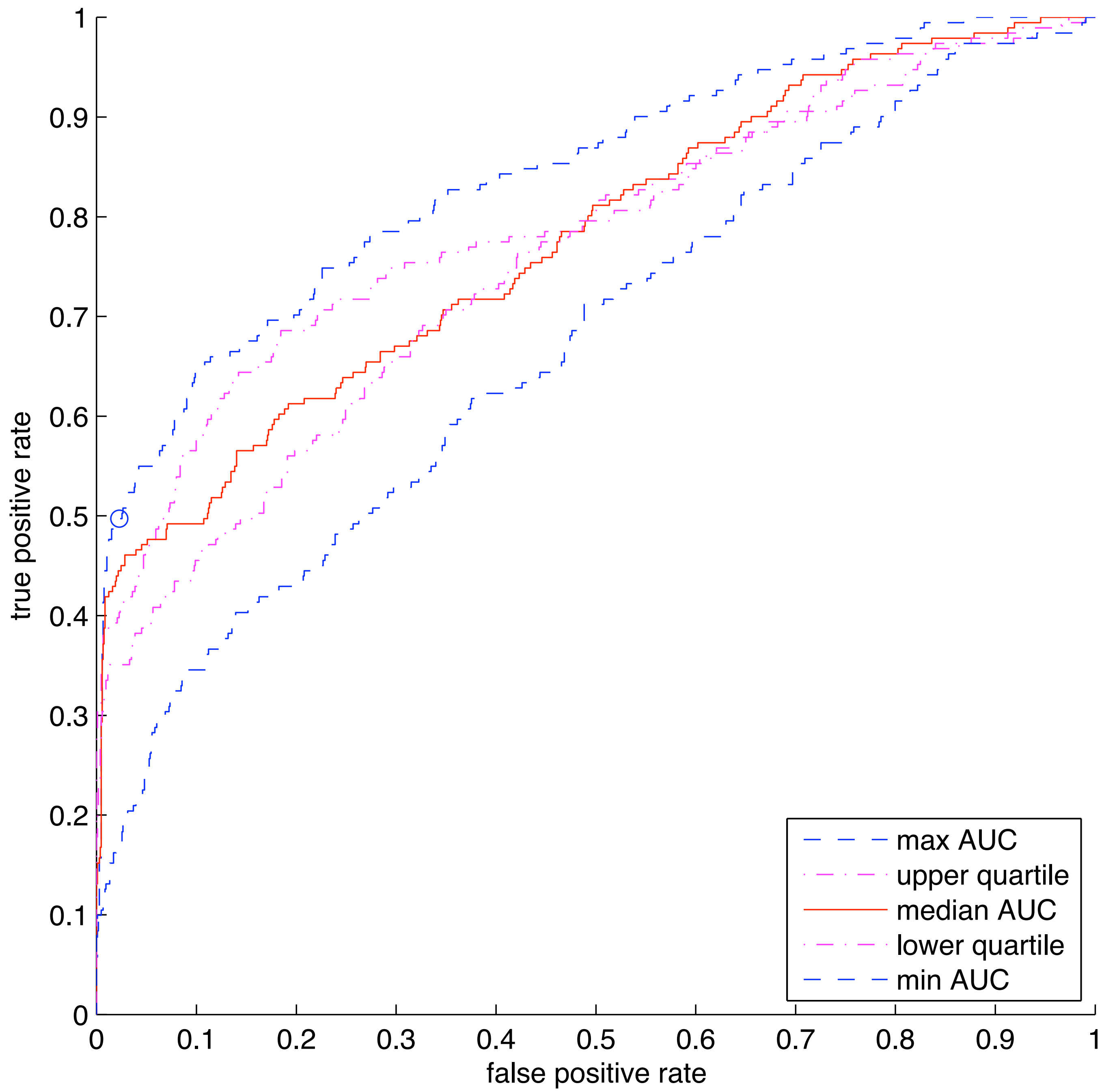
The bridge



The data

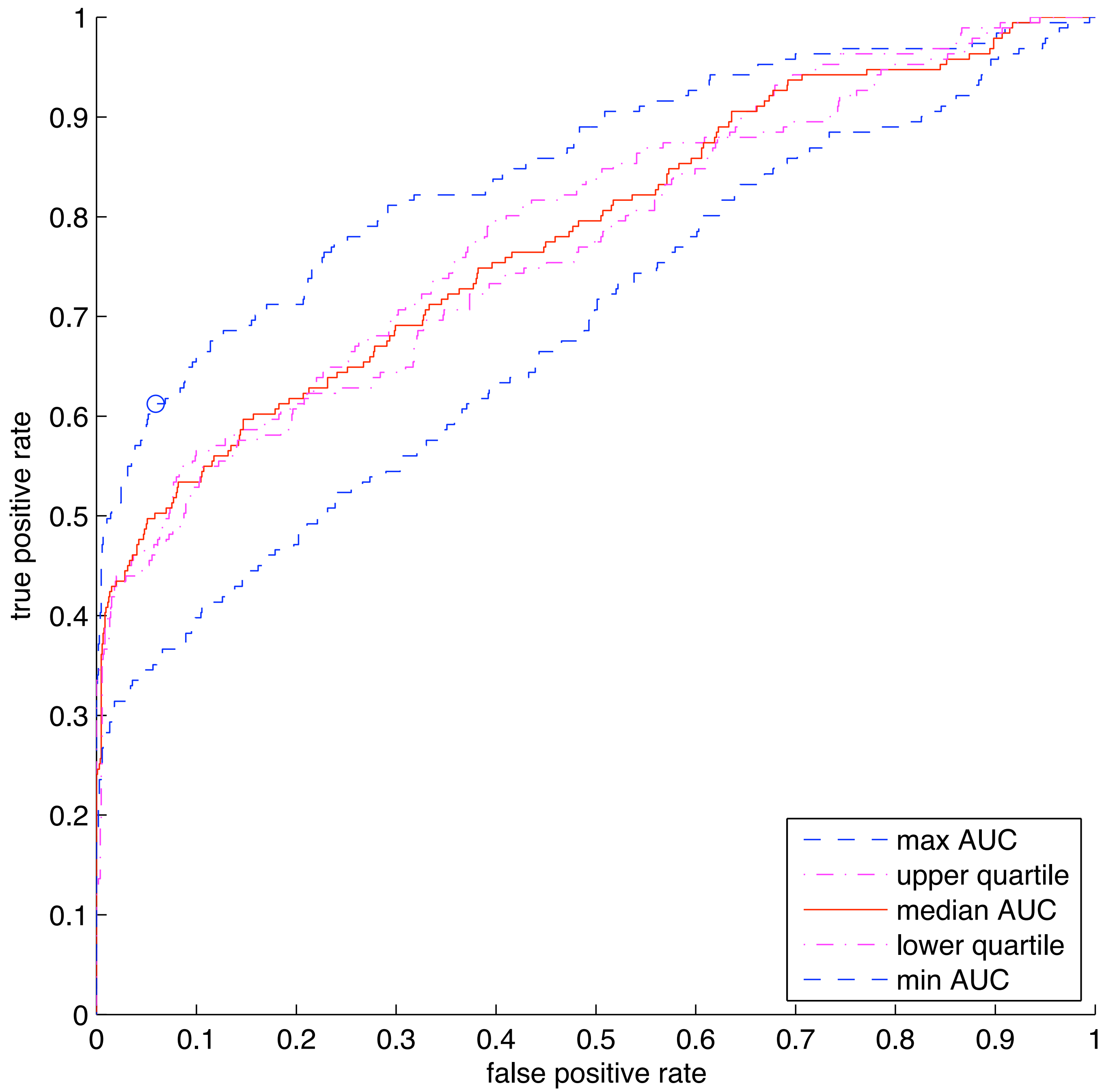
- **Wooden model bridge with 15 wired sensors**
  - 2509 measurements of 32 seconds each
  - 256 Hz sampling frequency
  - Damages simulated with small weights attached to the bridge: most of the measurements made without them
  - Every other measurement used for training...
- **Feature extraction**
  - 60 monitoring frequencies: 2, 4, 6, ..., 120 Hz
  - 15 sensors => 105 sensor pairs
  - Feature space: 6300 transmissibility features

Damage detection ROC



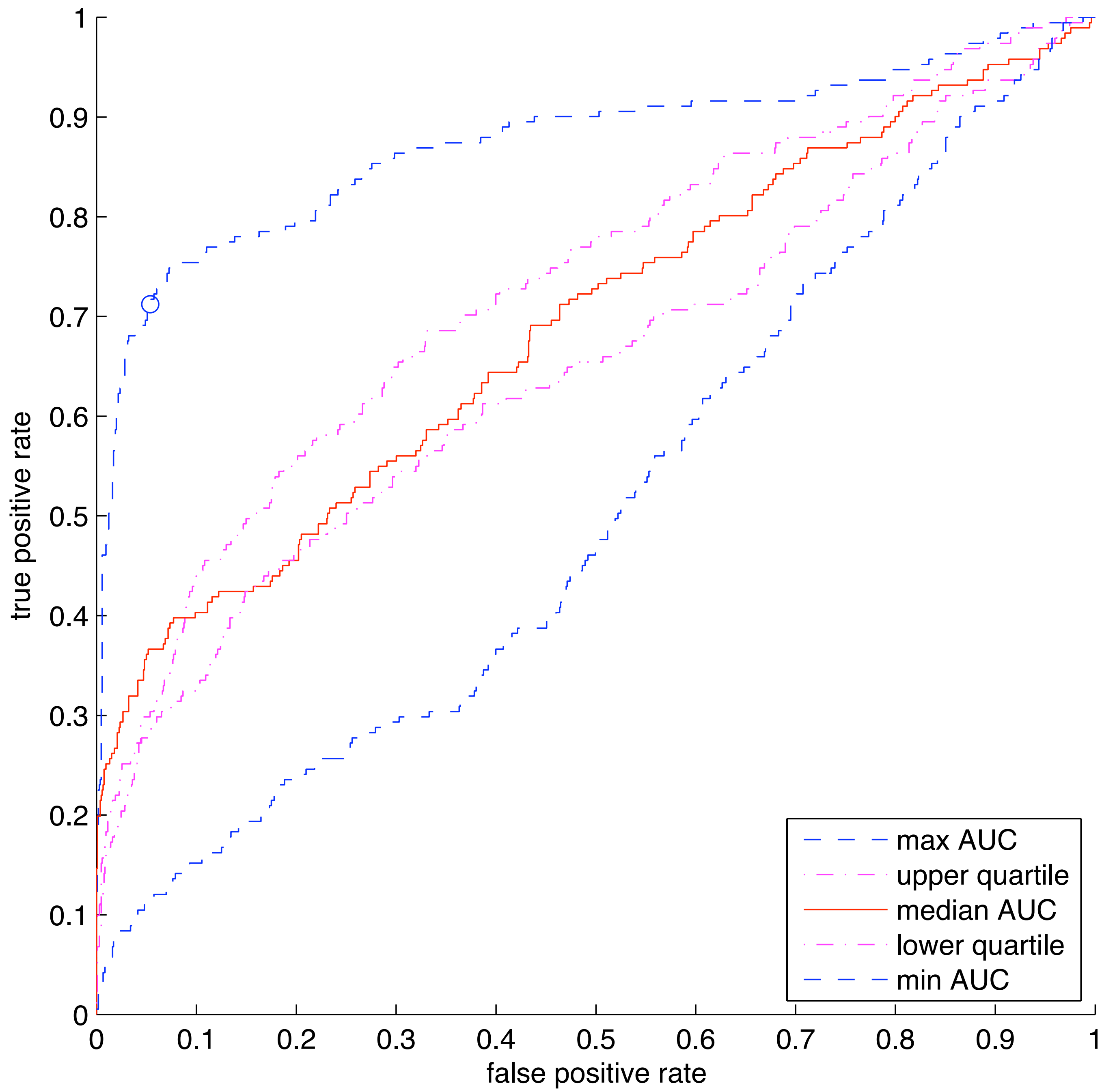
- **512 random features by QAM**

Damage detection ROC



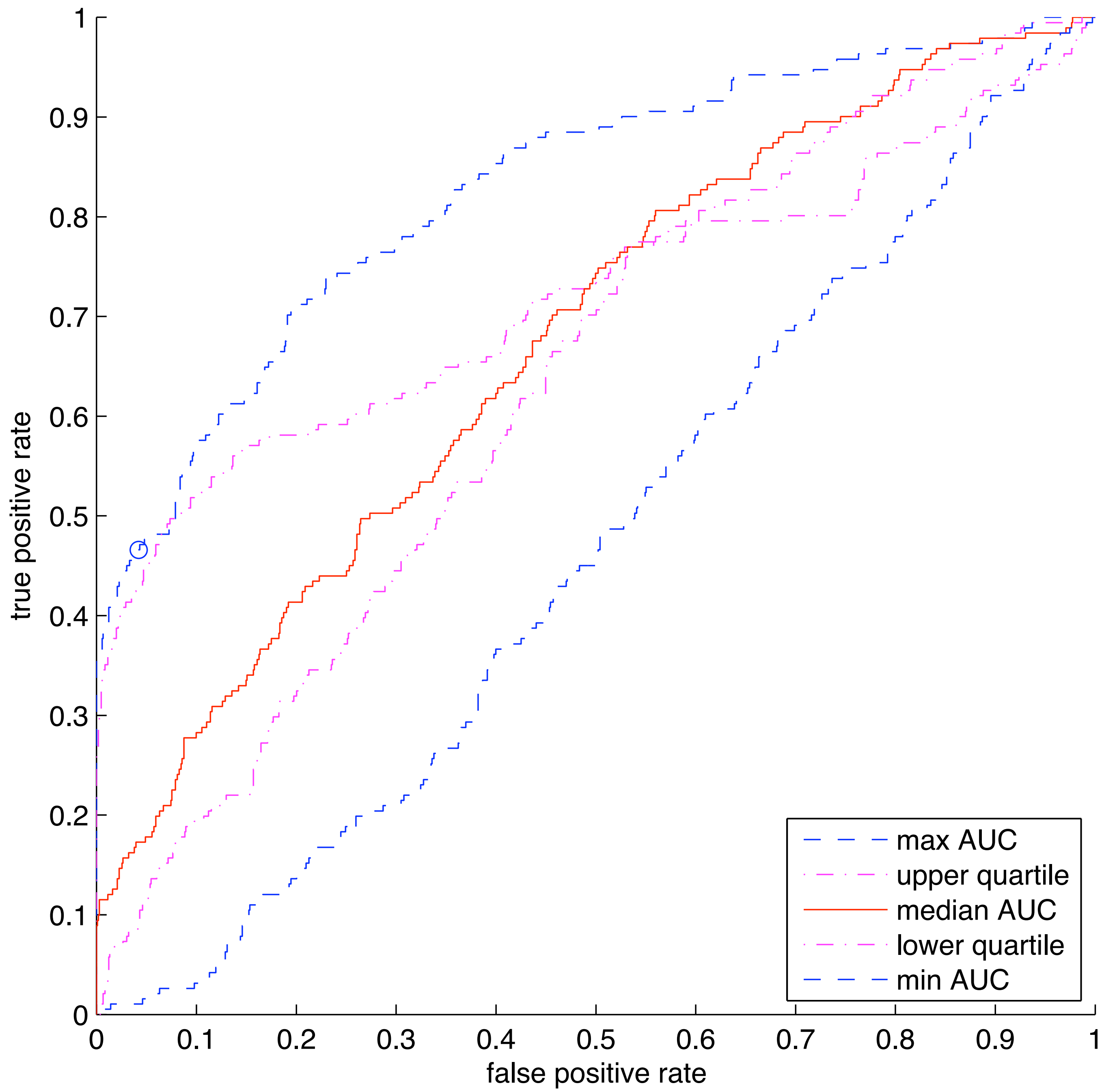
- **512 random features by Goertzel algorithm**

Damage detection ROC



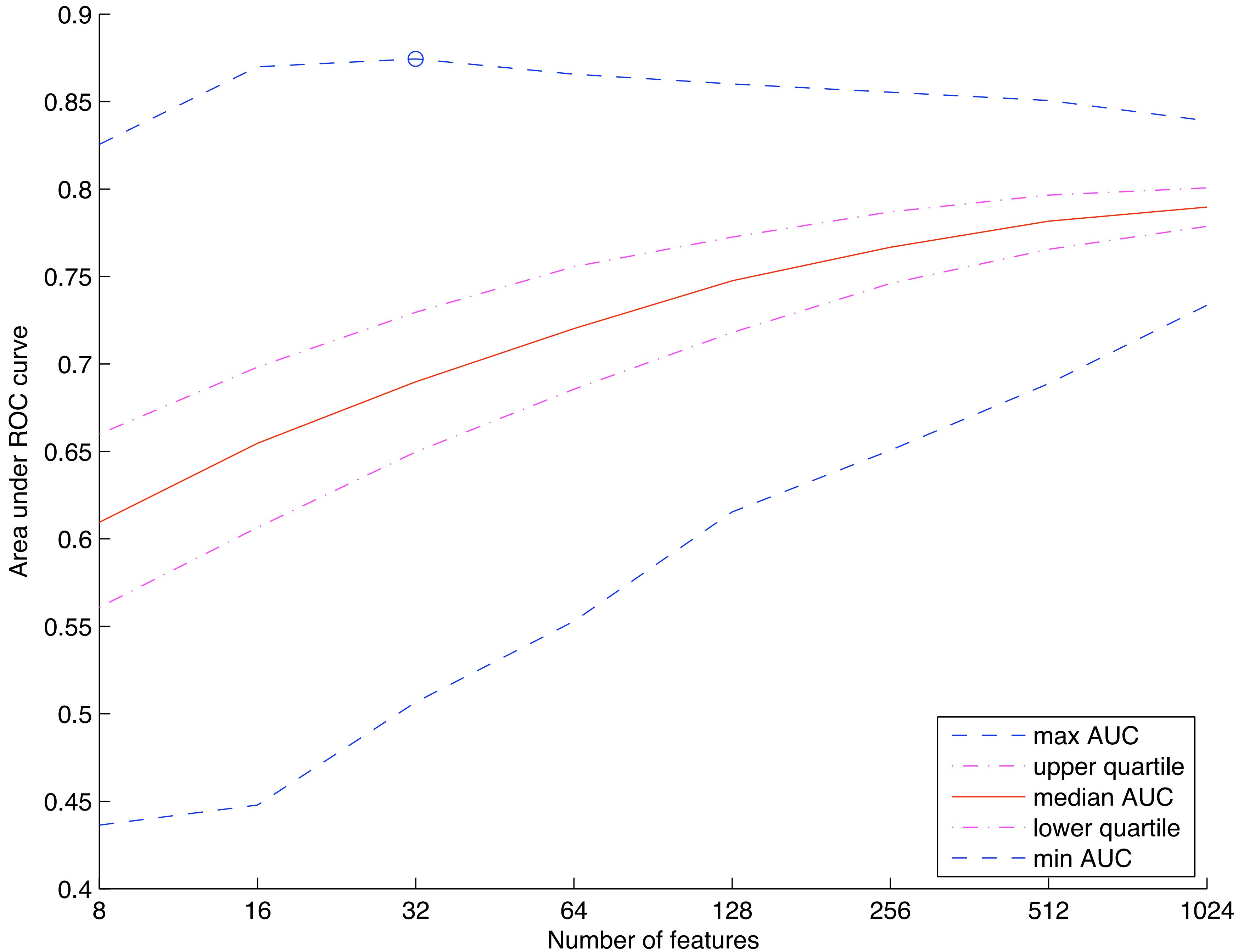
- **32 random features by Goertzel algorithm**

Damage detection ROC



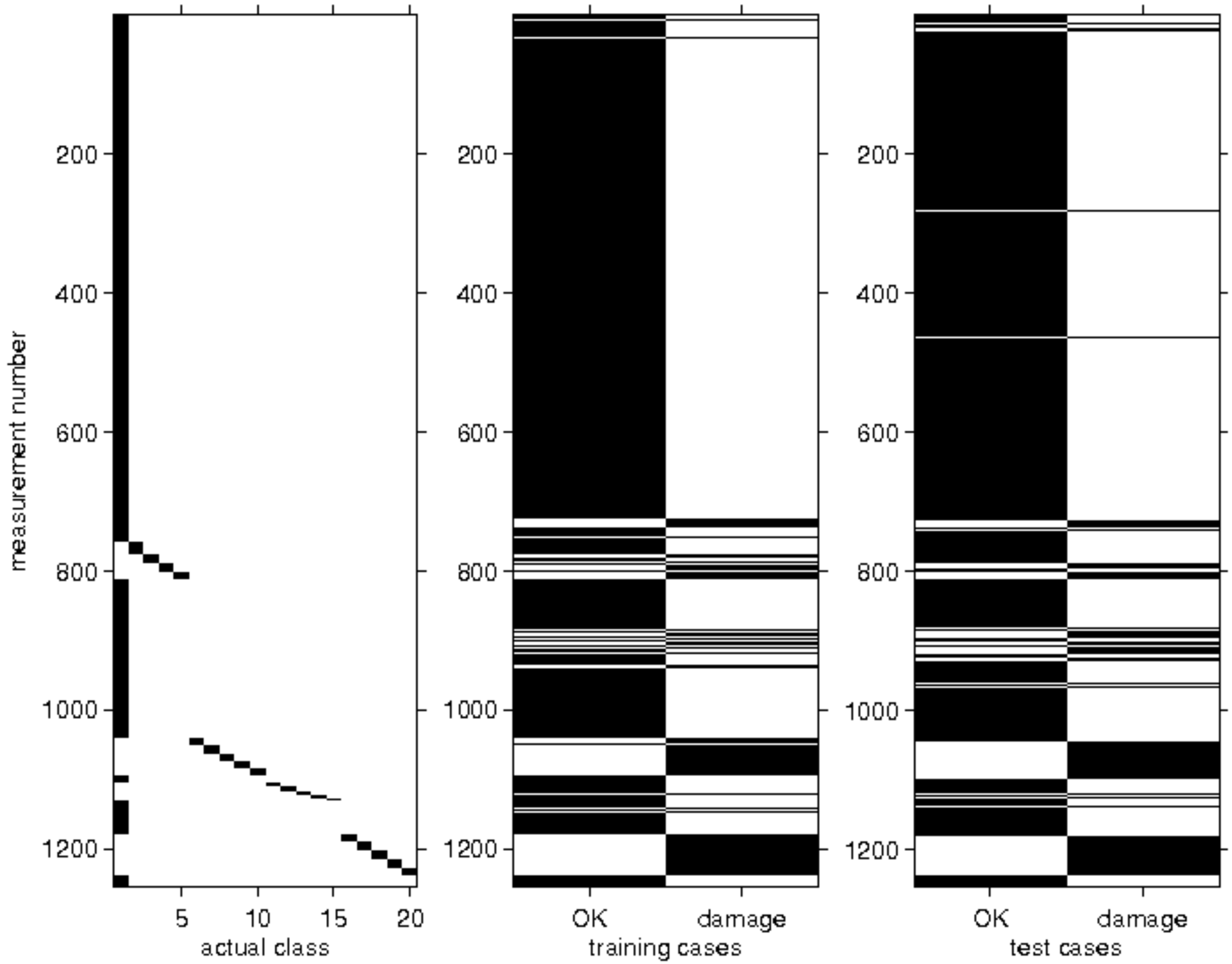
- 32 random features by QAM

Area under ROC curve



- **0.87 reached with 32 features (Goertzel)**

Detection example



- **one of the best classifiers with 32 features**

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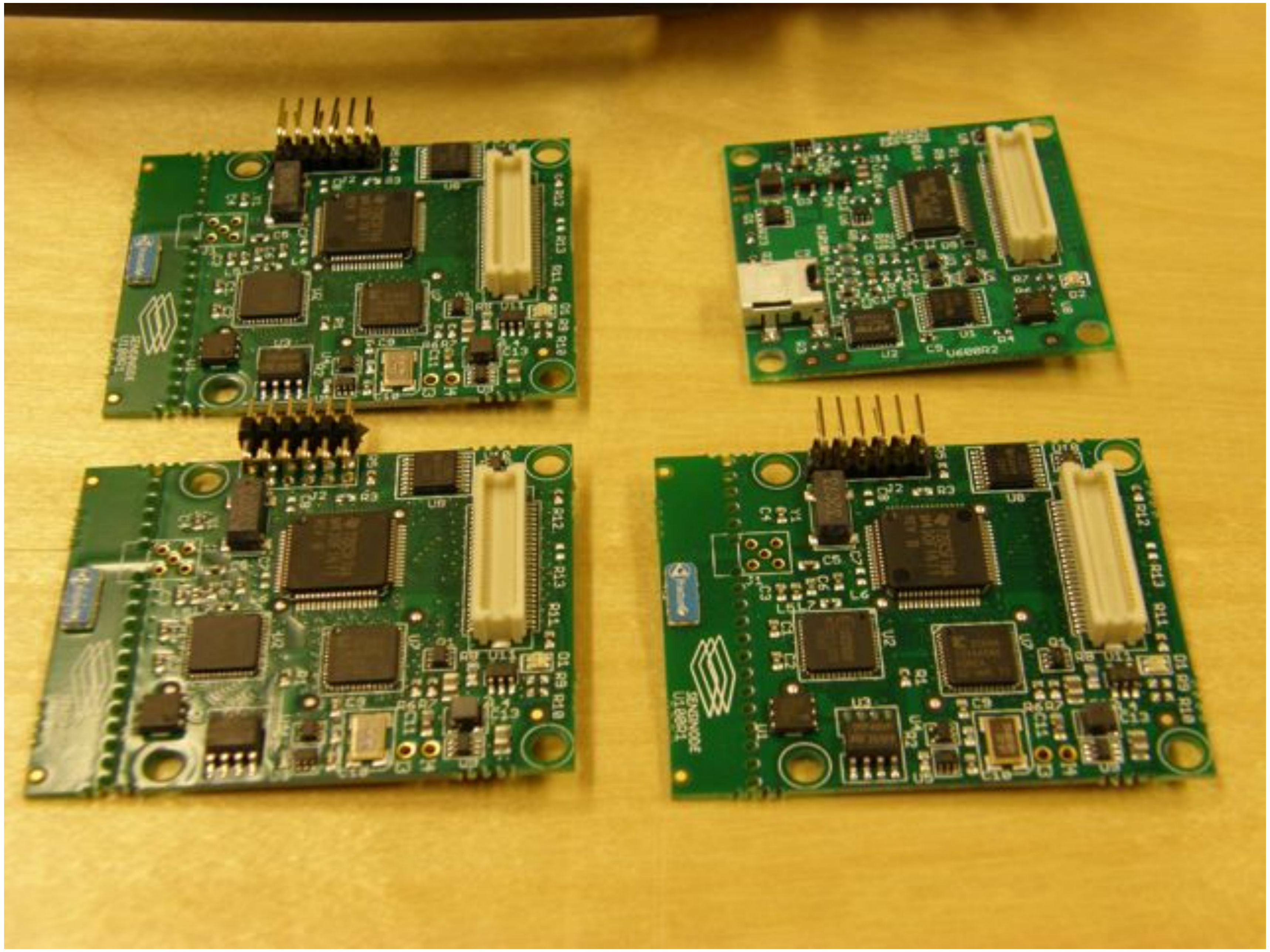
Summary

- **Used domain knowledge in computing features online**
- **Explored the feature space and found some small but relevant feature sets**
- **Feature selection made in a supervised setting – damages present in the training set**
- **Further work:**
  - develop methods for unlabeled data
  - implementation in actual wireless sensor nodes

Questions?



A good feature set