Energy and Bandwidth-Efficient Wireless Sensor Networks for Monitoring High-Frequency Events

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Motivation

- **Wireless sensor networks are increasingly being deployed for applications that require monitoring events at high-frequency:**
  - **Physical activity monitoring**
  - **Structural health monitoring (SHM)**
  - **Fire event monitoring, Smart building**
  - **Acoustic-based monitoring**
  - **Other security and health related application**
- **Events of interest: damage in physical structure (building, aircraft, and so on), fire, snow level, etc.**

Motivation

- In some of these applications, sensors require continuous data collection at a high frequency (hundreds to thousands of Hertz) for efficient monitoring.
- However, sensors generate too much data for their radios in these applications, especially in those that involve audio, seismometers, imaging, and vibration.
  - In most cases, sensors cannot send that data even one hop in real-time, due to limited bandwidth. The sensors exhaust the given energy quickly.

Typical Solutions

- **Energy management issue.**
- **Hardware perspective:**
    - **Using rechargeable battery and energy harvesting technologies, designing dynamic radio ranging techniques and efficient radio-wakeup module, etc.**
- **Software perspective:**
    - **Employing sampling techniques:**
        - **Adapting node's sampling rate (i.e. how often it is required to sample during a particular time interval).**
        - **Adapt a node's schedule (i.e. when and how long it is required to sample).**
        - **The samples acquired at different sampling rates are sent**

Difficulties in Existing Solutions

- **Sensors cannot take actions independently to adapt their rates and intervals. They all rely on a central unit (or a sink) that knows everything (signal complexities at all of the sensor positions) and periodically transmits sampling rates to them.**
  - **It is difficult to assign sampling rates or allocate bandwidth to sensors in a specific region where an interesting event occurs (e.g., damage in a structure, fire in a building)**
  - **All the samples acquired at different sampling rates should be sent**

Difficulties in Existing Solutions

- **The centralized or semi-distributed solutions may not represent an accurate picture of events (changes), as a WSN is characterised by**
  - **Dynamism, hostile environment deployment**
  - **Large scale or deployment in large monitoring environments**
  - **Imprecise and noisy observations.**
  - **The presence of an event is dynamic, some events may not appear once in hours, days, months, even years, e.g., damage in structures, fire, snow level, water level, natural disaster**
  - **Limited communication, computational, storage, and energy resources.**

Requiring autonomous adaptive sampling regarding the detection of events!

Proposed Approach: e-Sampling

- An event-sensitive adaptive Sampling and low-cost monitoring, which leads to reduced resource usage in WSNs in two-stage
  - 1st stage: Each sensor has "short" and recurrent "bursts" of high-rate sampling, and samples at a much lower rate at any other time
    - Depending on the analysis of the frequency content of signals, whenever one of the short intervals of high-rate sampling is longer than normal, possibly due to the presence of an event, the frequency content of signals becomes important.
    - The frequency content is analyzed for the sampling rate selection
  - 2nd stage: Such frequency content at an interval is analyzed for an event detection and monitoring

The Problem

- Given a set *S* of *N* sensors for monitoring events,
  - Each sensor s_i has actions it can perform, and these actions denoted by $A_i = \{R_i^1, R_i^1, \ldots, R_i^a\}$ represent sampling rates that s_i opts to perform at any particular point of time within network lifetime, and adjusts its interval. This means that s_i is allowed to adjust its actions by analyzing its recent samples of high frequency content and the samples it believes it will observe.
  - **Key constraints:** (i) action selection constraint; (ii) energy constraint; (iii) computational complexity
  - **Key objectives:** minimize required energy cost of the network, event monitoring latency, and maximize lifetime

Design of e-Sampling

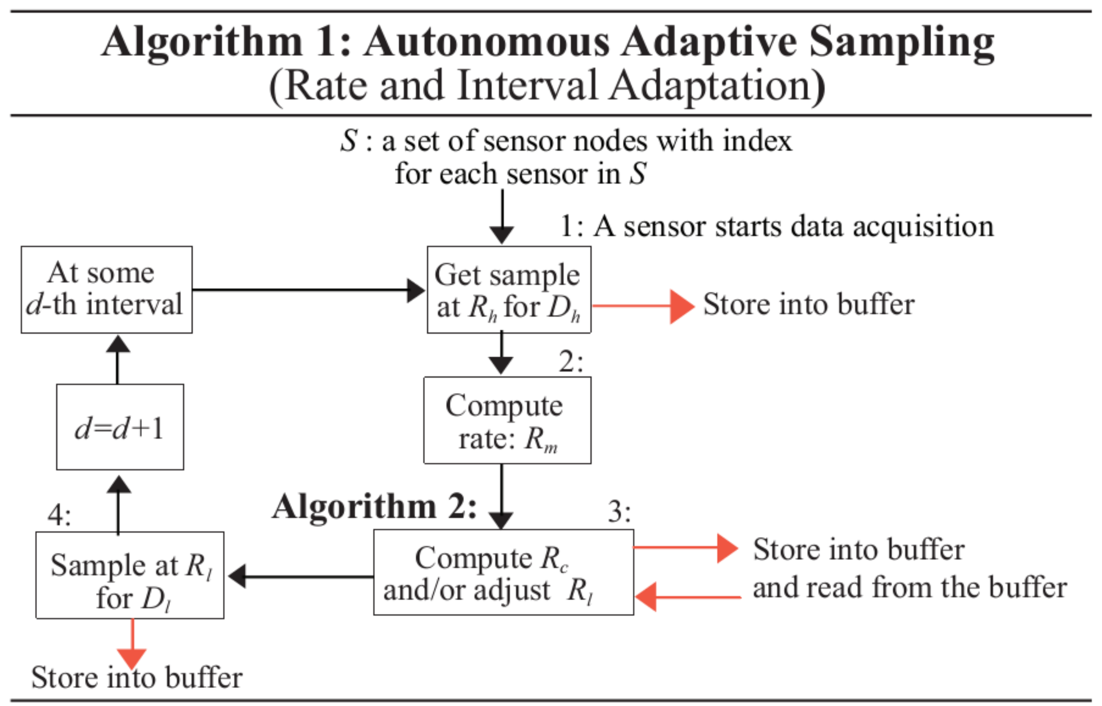
- **In the beginning of an interval *D*, sensors start short and recurrent bursts of sampling at a high-rate (R_h), and examine these samples to analyze high frequency content (F_h)**
- **Each interval *D* consists of two sub-intervals:**
  - **D_h starts with a short investigative sub-interval in which an high sampling rate R_h is adopted**
  - **D_l (the remainder of the interval in each time interval) starts when the sampling rate is adjusted to a lower rate (R_l), based on findings in the F_h**

Design of e-Sampling
(Two stages data reduction)

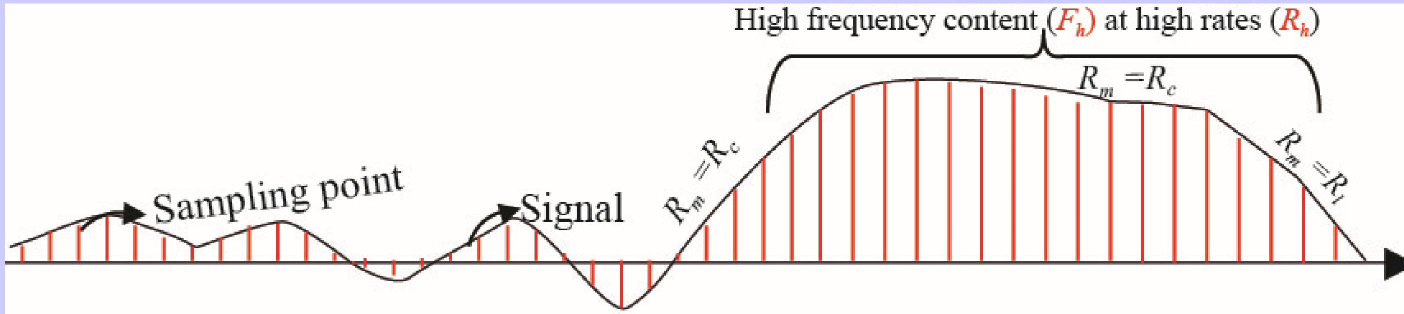
```
DecentralizedControl{                //1st stage data reduction
 While (True) {
   S.RateComp in D_h = True {  // start Sampling Rate Computation at the
                                  beginning of the system or at a certain interval
   Run the Algorithm 1;       // Sampling rate and interval adaptation
   Compute new R_c;       //set a new sampling rate
   Compute D_l;}}}         //set the duration for the new rate
ComputeEventIndication{          //2nd stage data reduction
   Run the Event Indication Algorithm
     If indication.Strength ≥ 40%
          transmit the indication;
     else transmit an acknowledgment;}
```

First Stage Data Reduction

- **Proposed an autonomous adaptive sampling algorithm**
  - **Step 1: each sensor first starts acquiring samples at a high rate, and stores them into the buffer. These samples are used to analyze high frequency content (F_h)**
  - **Step 2: the sensor computes the minimum sampling rate, R_m**

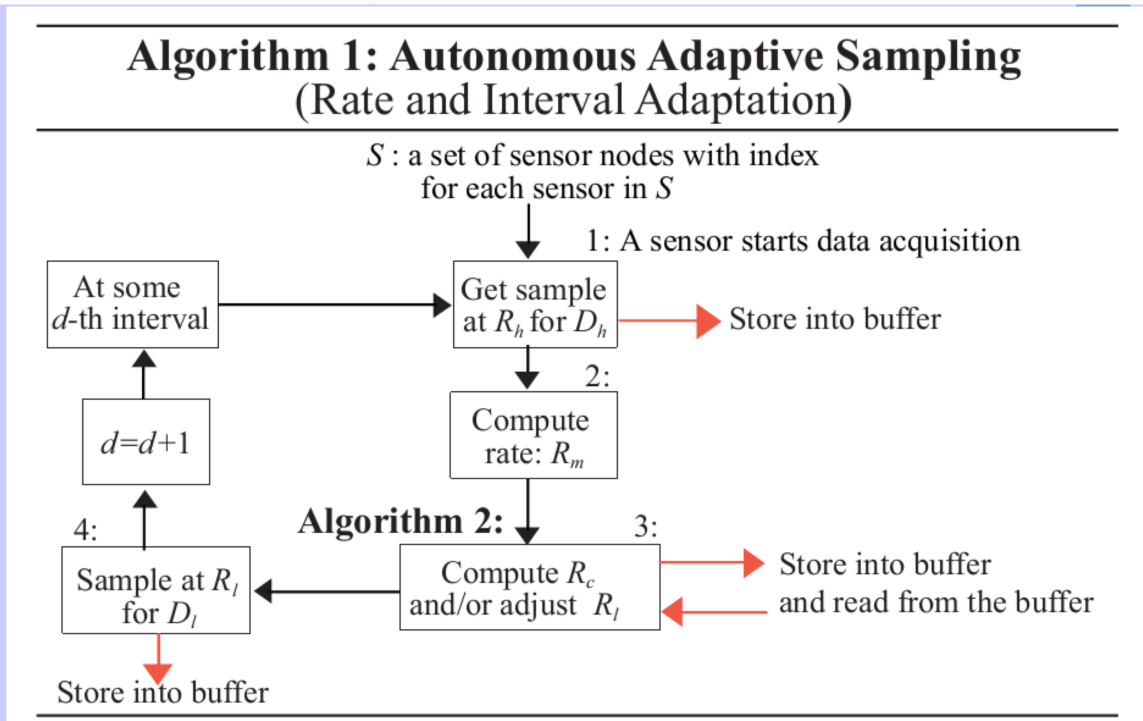


First Stage Data Reduction



– **Step 3:** **Algorithm 2, which helps to make a decision whether or not the current rate should be continued (*$R_m = R_c$*)**

OR the current rate should be adjusted to a lower rate (*$R_m = R_l$*)

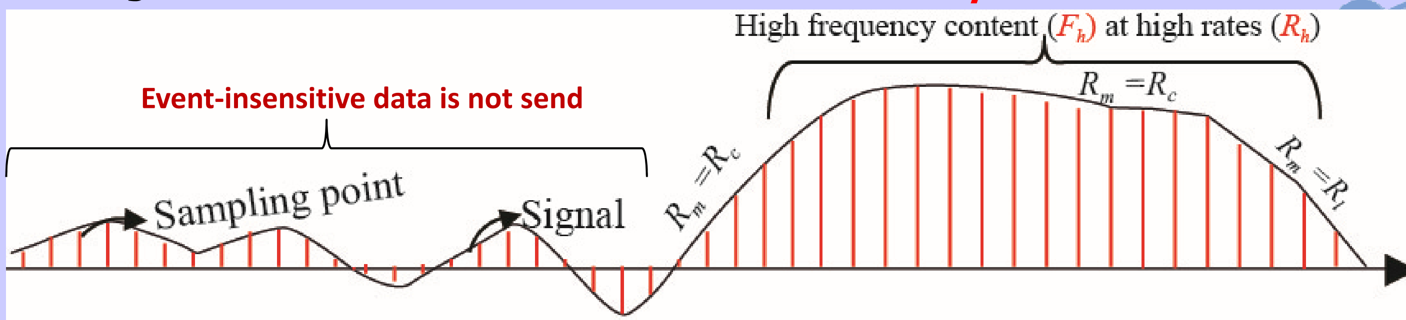


Step 3: Rate Selection Algorithm

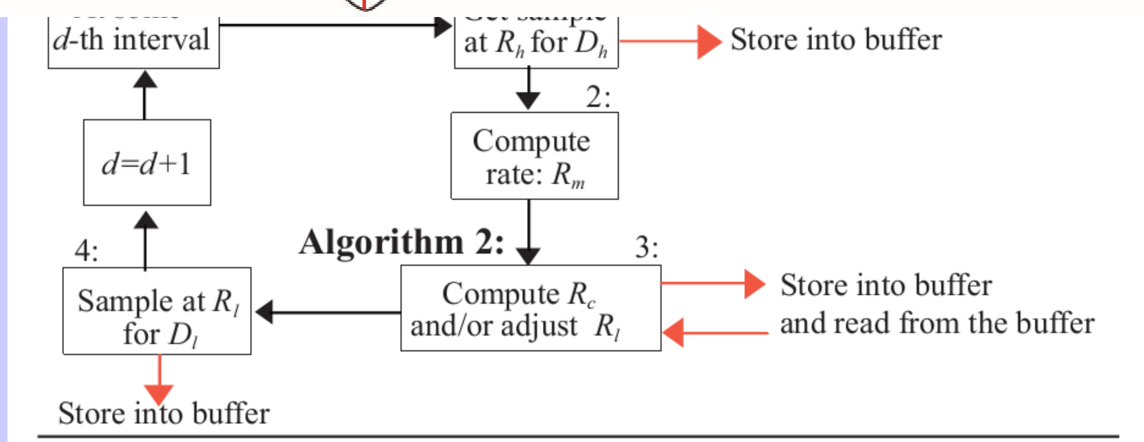
- **All of the acquired samples are split into frequency bands at a sensor's current sampling rate to estimate high frequency content:**
  - **The wavelet packet decomposition (WPD) technique is used for this purpose, which is leveraged to break the signal into frequency bands.**
  - **The wavelet packet transform decomposes the set of samples into separate frequency bands by recursively applying high-pass and low-pass filters.**
- **Based on the decomposition, whether the F_h is important or not for further high rate sampling and event detection, can be known.**

First Stage Data Reduction

– **If F_h is still important (there is possibly an event), the sensor continues sampling at the current rate, $R_m = R_c$; Otherwise, it adjusts the rate to a lower rate, R_l.**



– **After getting the lower rate, the sensor continues sampling at this rate in step 4, until the next *d*-th interval.**



2nd Stage Data Reduction: Event Indication

- **Any monitoring applications that require high frequency sampling can use the proposed adaptive sampling algorithm and reduce data in the 1st stage.**
- **However, after data reduction in the 1st stage, it is still infeasible for a resource-constrained WSN to transmit the whole set of F_h.**
  - **We use the sensor decentralized computing to provide an indication shortly based on the F_h, i.e., analyzing those ranges of samples acquired at a high rate .**

2nd Stage Data Reduction: Event Indication

- **Each sensor is enabled to compute a lightweight indication of the presence of an event**
  - **A significant change in the frequency content (called event-sensitive data) indicates that a possible event occurred in a given monitoring application**
  - **Further data collection may required by in specific regions (e.g., which are located around the event)**
- **Otherwise, in the absence of the event, sensors further reduce data transmission (i.e., uninteresting data) toward the sink.**

2nd Stage Data Reduction: Event Indication

- **We use structural health monitoring (SHM) as a representative high-rate application and use the adaptive sampling algorithm for SHM.**
  - **In a typical SHM system, the objective is to monitor structures (e.g., buildings, bridges, aircrafts, nuclear plants, etc.) and to detect possible events (e.g., damage, cracks) of them at an early stage, which prevails throughout the engineering domains.**

2nd Stage Data Reduction: Event Indication

- **A sensor has all of the acquired samples sequenced in the database.**
  - It first distinguishes the samples in F_h and then reads them from the database, i.e., only the samples in F_h are processed to extract an indication on an event.
  - The indication decision is normalized and graded as the percentage of the strength of the event detection, e.g., very Low ≤ 20%, Med ≤ 40%, High ≤ 60%.
  - If the strength is very Low, a sensor does not make a pairwise comparison, and does not need to transmit the samples toward the sink. Thus, the amount of transmission is reduced significantly.

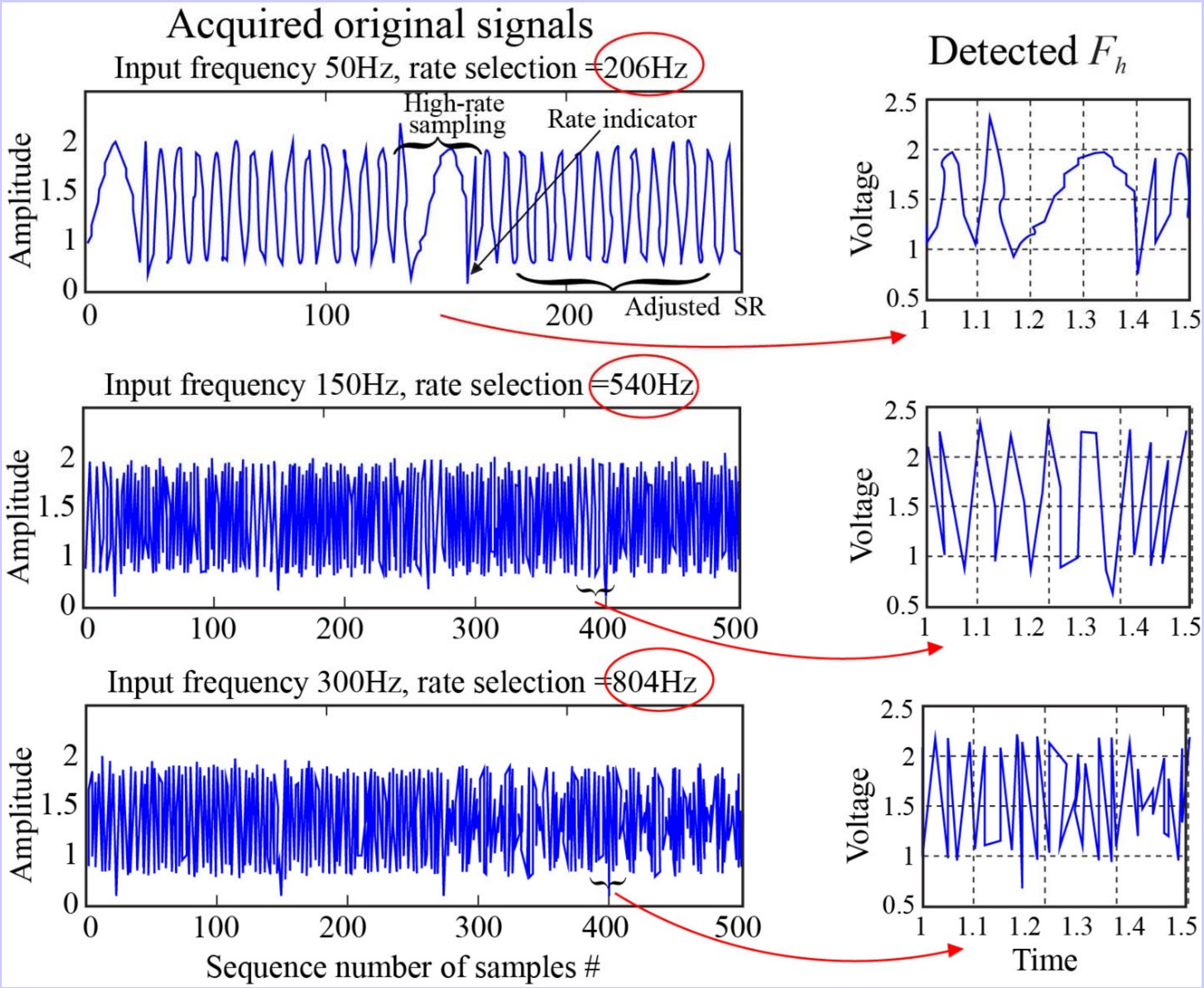
Evaluation

- **We adopt real datasets that consist of the vibration signals collected from a sophisticated SHM system, deployed on a high-rise Guangzhou National TV tower (GNTVT).**
  - **These datasets are collected by a set of 200 and a set of 800 sensors.**
  - **The core of our simulation relies on the sample set data structure that contains data collected at a low to high sampling rate.**

Evaluation

- **Simulations are performed with Matlab Toolbox using a finite element model (FEM) of a structure, and in a 50m* 400m rectangular field**
  - **Different levels of physical event (such as damage) information are injected at 10 sensor locations (by modifying input signals randomly in the datasets).**
- **More schemes are implemented:**
  - **(i) SPEM: this is a SHM scheme with fixed rate sampling. (ii) FloodNet : a decentralized control algorithm for information-based adaptive sampling; (iii) QAS: a quality aware adaptive sampling (iv) e-Sampling-C: this is a semi-centralized version of e-Sampling that excludes the 2nd stage data reduction**

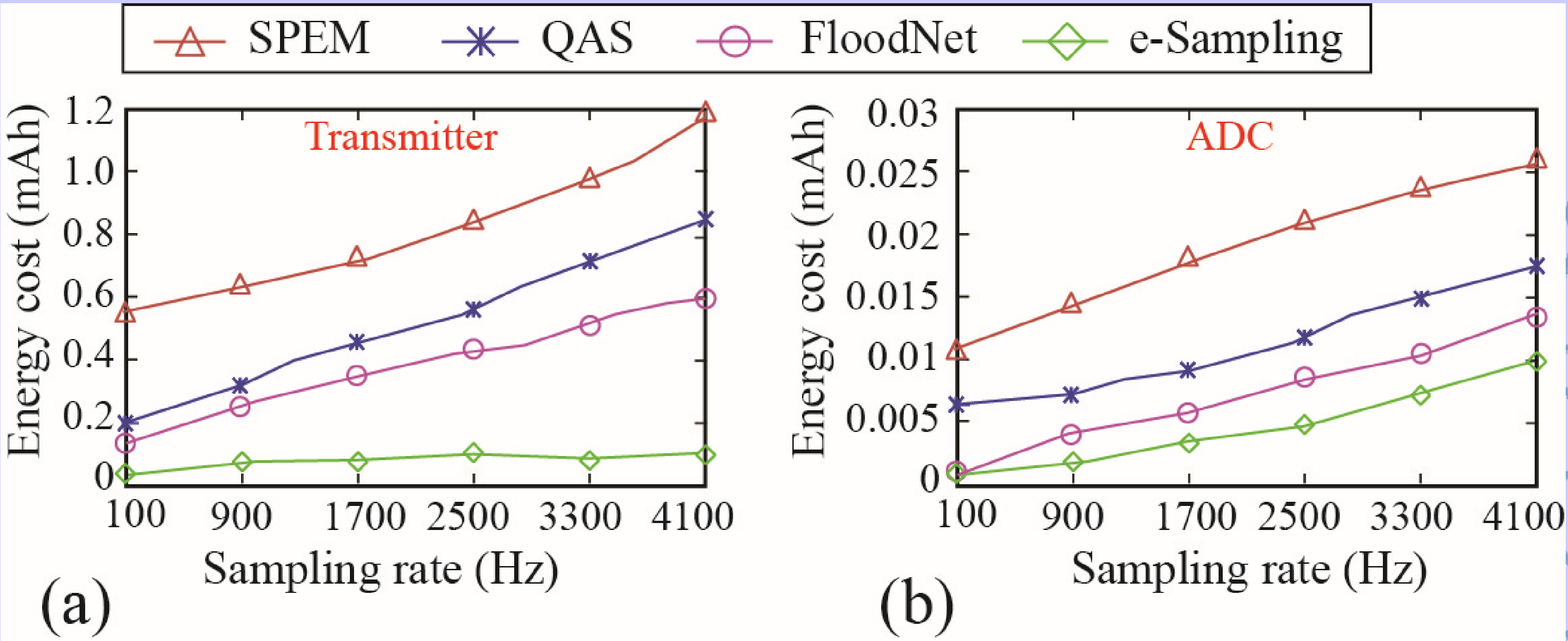
Results (1)



These are event-sensitive samples that can be analyzed for further sampling rate adaptation and event detection.

At any other time, the amount of data transmission is minimized to reduce energy cost

Results (2)



Energy cost (of transmitter and ADC) of a sensor (the 6th sensor) at different sampling rates calculated over a monitoring round.

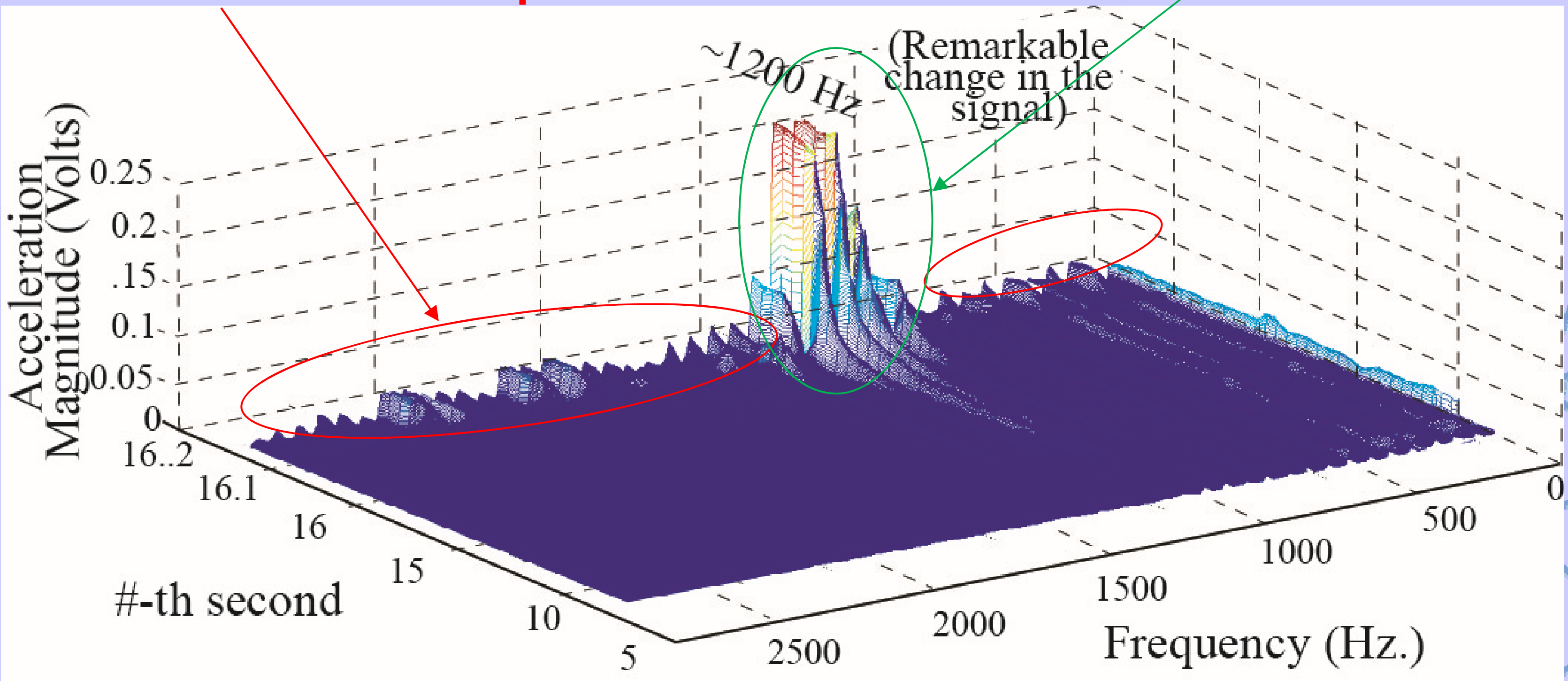
Real Implementation

- **A proof-of-concept system is implemented using the TinyOS on Imote2 sensor platforms.**
  - **A specially design a test infrastructure is used in our lab and 10 mote are deployed on it.**
  - **Each mote runs a program (implemented in the nesC language) to process the acceleration signal acquired from on-board accelerometers (LIS3L02DQ).**
  - **The digital acceleration signal is acquired within frames of 4,096 data points and is then stored in the local memory for each round of monitoring.**
  - **We inject events at the 4th sensor location by removing the plate from the 4th floor of the structure to observe the sampling rate adaptation and event indication.**

Result (3)

Event-insensitive samples: no need to transmit these samples

Event sensitive samples: Detected F_h

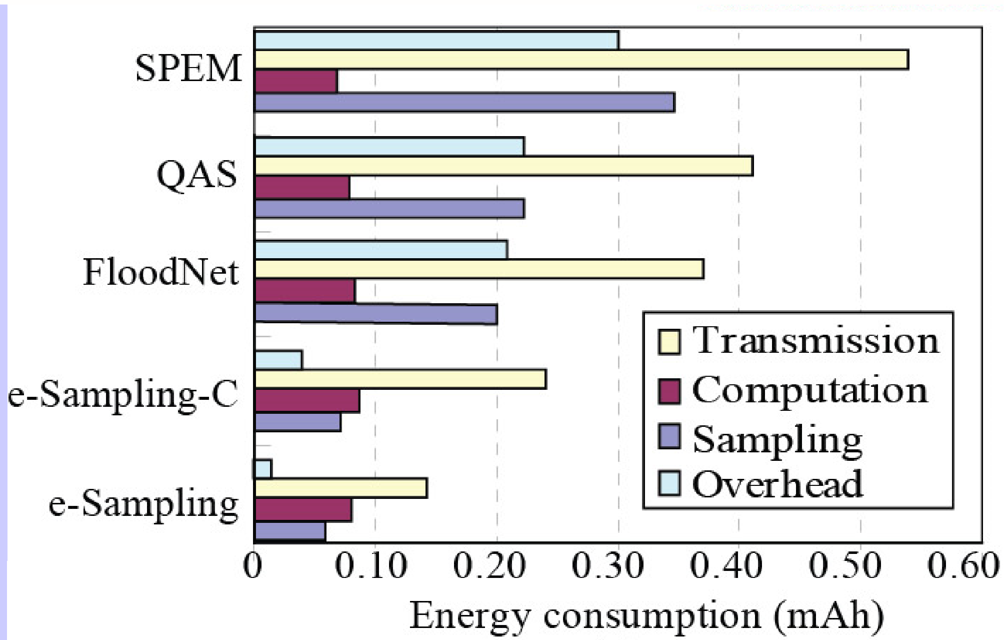


Waterfall plot of frequency content vs. time, showing that the high frequency content is detected, which are used for event detection

Result (4)

Enegy Saving	Deployed sensor no. #									
	1	2	3	4	5	6	7	8	9	10
In the 1st stage	42.3%	27.2%	15.4%	12.1%	21.9%	25.7%	33.8%	62.1%	62.2%	75.1%
In the 2nd stage	53.8%	48.2%	22.5%	13.2%	17.3%	23.5%	43.1%	59%	83.1%	85.2%
Energy Wasting	(-) 4.2% (on average)									

Based on the data reduction through the adaptive sampling algorithm, the overall energy consumption in different approaches is analyzed



Conclusions

- e-Sampling is an alternative to the traditional event-insensitive schemes, is capable of high-rate data acquisition and multi-hop wireless transmission.
  - It supports diverse WSN applications, while it is able to run on small and low power micro-controller-based sensor nodes.
- Future studies will consider its perfroamcne in monitoring different high-frequency events and the event detection accuracy.

Thank you for your attention

Q & A

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