Scalable Data Acquisition for Densely Instrumented Cyber-Physical Systems

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Outline

- Introduction
- Background
  - Dominance-based MAC protocols
  - Quantity aggregation
  - Interpolation
- Using a physical model in interpolation
- New interpolation algorithm
  - Evaluation Result
- Conclusion

Introduction

- As a result of advance in electronics technology, sensor design, wireless communication
  – The cost of a sensor node drops toward zero

↓

Economically feasible to densely deploy networks with sensor nodes

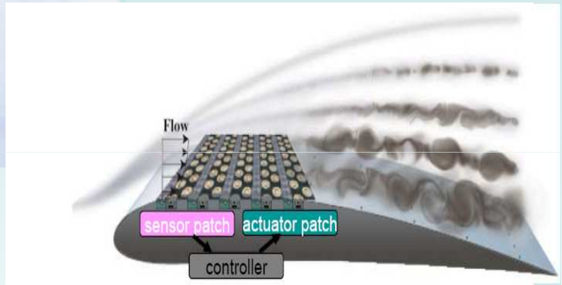
- Very dense networks :
  – Better resolution of the physical world
  – Better capability of detecting an event

Application of Dense Networks

- Structural health monitoring (SHM)
  - Visual inspections impose high costs and inconvenience
  - Convertes a structure into a ‘smart’ one with state-of-the-art sensing technology
  - Early detection of damage can save money and lives
    - Reduced Maintenance
    - Increased Longevity (Health)
    - Improved Safety

Application of Dense Networks

- Active flow control
  - Aircraft industry



- Biomechanical Aerial Technology System (BATS)
  - Be constructed entirely of distributed systems

Problem

- Huge number of nodes ➡ Huge Challenges
  - Interconnectivity
  - Data gathering
  - Data processing

- Problem:Design an algorithm for acquiring data in a dense network considering

  (i) Sensor readings originate from different sensor nodes

  (ii) Very large number of sensor nodes

  (iii) Dense network

  (iv) In a single broadcast domain

Approach...

- An approximate representation of sensor readings

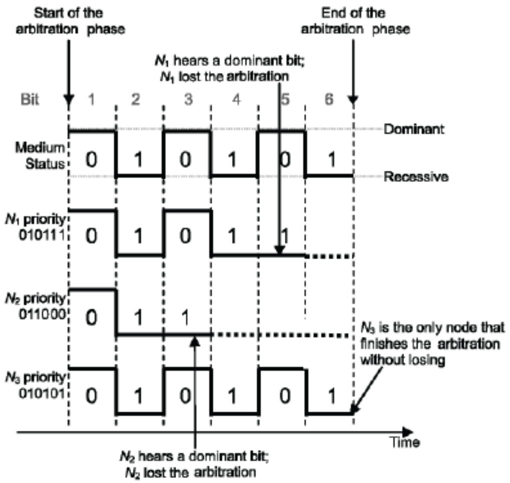
- An Interpolation of the physical system
  - Based on *all* sensor readings
  - Scalable

Contradicting?

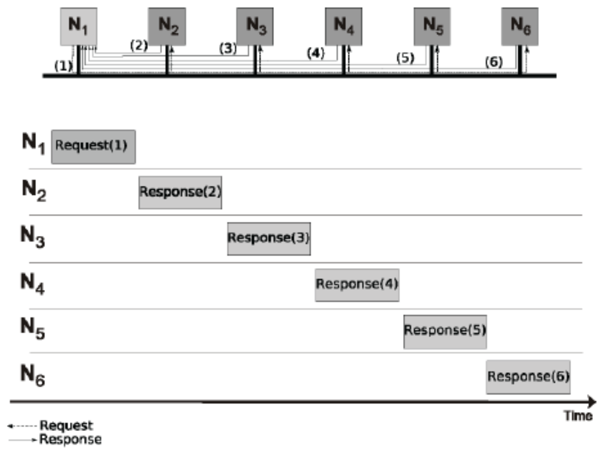
Using quantity aggregation and Interpolation technique based on dominance protocol

Background

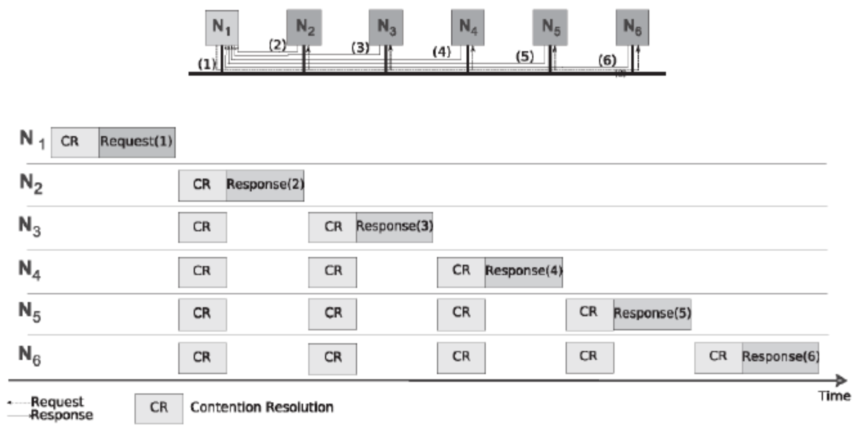
- Dominance-based Medium Access Control (MAC) protocols
  - Simultaneous "non-destructive" transmission of information in the same broadcast domain
  - Each node sends its unique contention field bit by bit starting from MSB
  - The bus behaves as a logical wired-and
    - Recessive bit (a logical '1')
    - Dominant bit (a logical '0')
- Implementation:
  - Wired Controller Area Network (CAN) bus
  - Wireless: WiDom



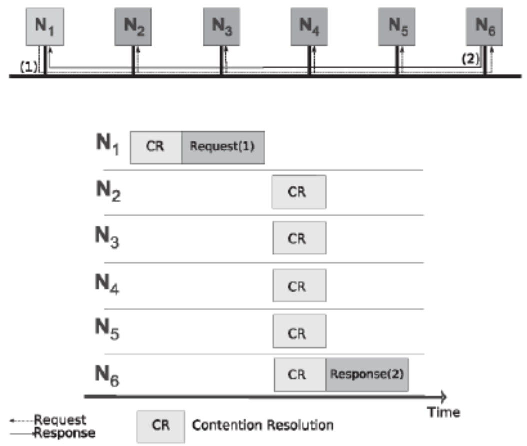
(a) CAN arbitration



(b) Naïve algorithm (TDMA-like MAC)



(c) Naïve algorithm (CAN-like MAC)



(d) Novel algorithm (CAN-like MAC)

Quantity Aggregation

- Based on *dominance protocols*
  - Possible to gather certain aggregate quantities (MIN, MAX or COUNT)
    - Time complexityof the method is independent of the number of nodes
  - Possible to produce an approximate representation of all sensor readings
    - Due to spatially and temporally correlation of sensor readings

Interpolation

- Interpolation function:

$$f(x,y) = \begin{cases} 0 & if\ S = \emptyset \\ s_k & if\ \exists q_k \in S : x_k = x \wedge y_k = y \\ \frac{\sum_{k\in S} s_k \cdot w_k(x,y)}{\sum_{k\in S} w_k(x,y)} & otherwise \end{cases}$$

$$w_k(x,y) = \frac{1}{(x_k - x)^2 + (y_k - y)^2}$$

- Error of the interpolation at sensor node *Ni*

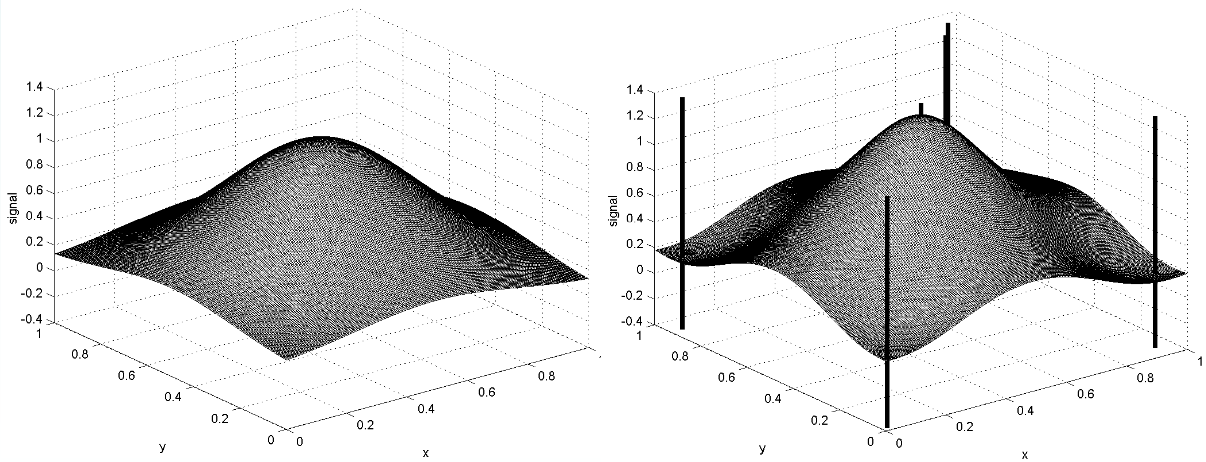
$$e_i = |s_i - f(x_i, y_i)|$$

- Maximum overall error

$$e = \max_{i=1..m} e_i$$

The Basic Interpolation Algorithm

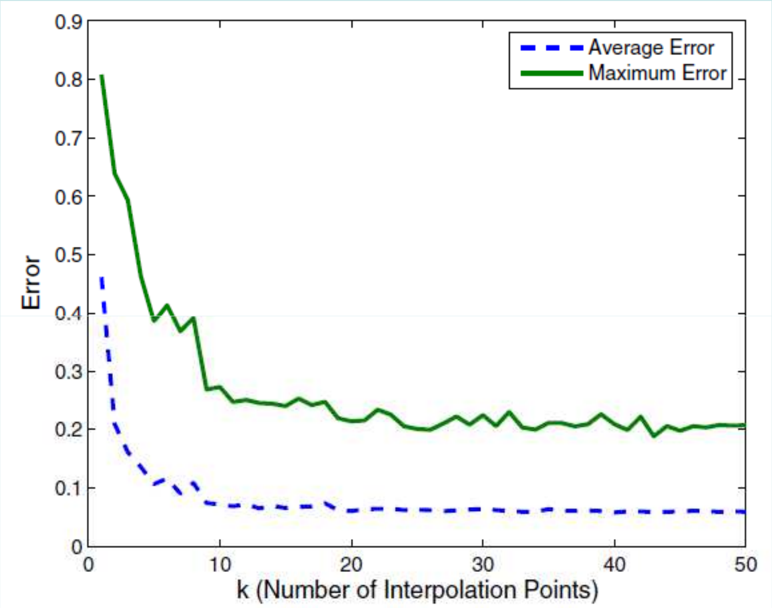
$S \leftarrow \emptyset$
for $j \leftarrow 1$ ***to k do***
calculate the interpolation function $f(x_i, y_i)$ *based on S*
calculate e_j.
select a sensor node N_k *with the maximum* e_k, *that is* $e_k = e$. *This can* be achieved using the previous MAX computation.
the location and the sensor reading of N_k *forms a control points;* add this control point to S
end for



Evaluation

– Basic interpolationalgorithm

- Signal with slow changes (slower than the time execution of the algorithm)



- Fast changing signal?
  - Algorithm can not follow the changes in signal...

Proposed Solution

Embedding a model of the dynamics of the physical world in the algorithm

- The better the model, the lower the interpolation error
- What do we need?
  - A simple framework

    (i) Sufficiently expressive

    (ii) Execute efficiently

Proposed Model

Performing a linear transformation on each element in *S*

- Allows different operations to the signals
  - Increasing/ Decreasing
  - Scaling
  - Translation
  - Rotation

Framework

$S \leftarrow \varnothing$
for $j \leftarrow 1$ to k **do**
    calculate the interpolation function $f(x_i, y_i)$ based on S
    calculate e_j.
    select a sensor node N_k with the maximum e_k, that is $e_k = e$. This can be achieved using the MAX computation mentioned in Section II.
    the location and the sensor reading of N_k forms a control point; add this control point to S.
    for each element (x_i, y_i, s_i) **in** S **do**
        $xnew_i \leftarrow A_{1,1} * x_i + A_{1,2} * y_i + A_{1,3} * s_i + A_{1,4}$
        $ynew_i \leftarrow A_{2,1} * x_i + A_{2,2} * y_i + A_{2,3} * s_i + A_{2,4}$
        $snew_i \leftarrow A_{3,1} * x_i + A_{3,2} * y_i + A_{3,3} * s_i + A_{3,4}$
        replace the element (x_i, y_i, s_i) in S by $(xnew_i, ynew_i, snew_i)$
    end for
end for

Case Study

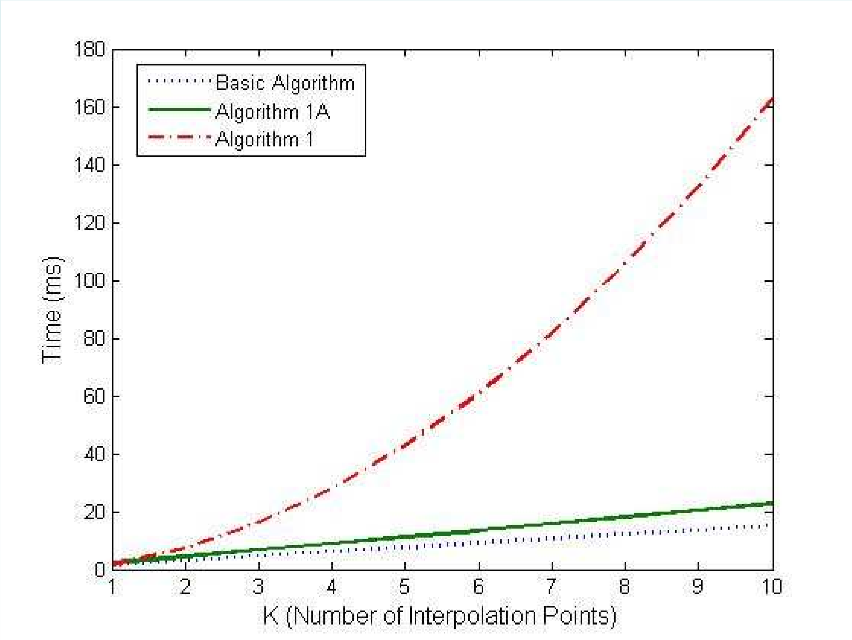
- Type of change in signal: Increment/Decrement
  - Updating control points with their differentials

$$
\begin{aligned}
&: \quad xnew_i \leftarrow 1*x_i + 0*y_i + 0*s_i + 0 \\
&: \quad ynew_i \leftarrow 0*x_i + 1*y_i + 0*s_i + 0 \\
&: \quad snew_i \leftarrow 0*x_i + 0*y_i + 1*s_i + g_i
\end{aligned}
$$

- Different algorithms
  - Having more information from the physical system ➡ simpler algorithm
    - Constant differential at each point ($O(k^2)$)
    - Equal, constant differential for all the points ($O(k)$)

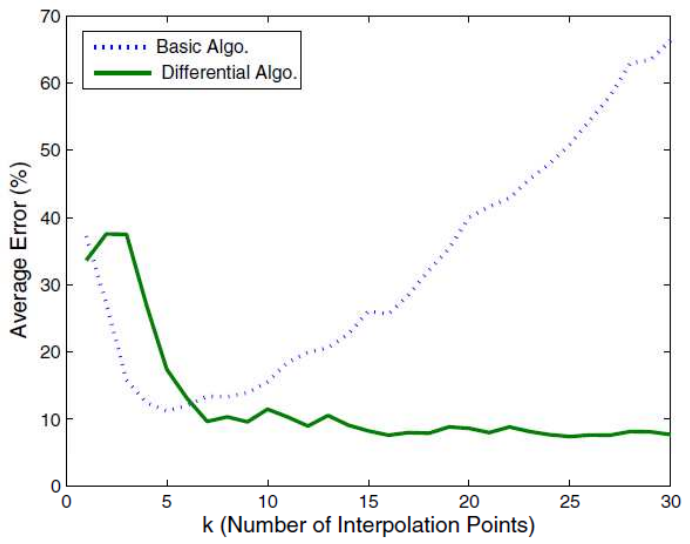
Evaluation (1/3)

- Execution time:
  - In a MicaZ sensor network platform
    - Using one of the microcontroller's real-time clocks

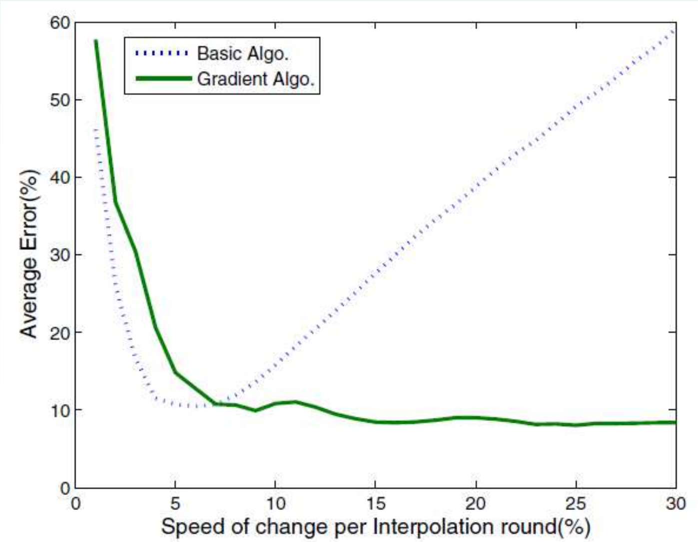


Evaluation (2/3)

- Average error
  - Dynamic signal with constant 4% change per interpolation round



  - Dynamic signal with random up to 4% change per interpolation round



Evaluation (3/3)

- K= 10

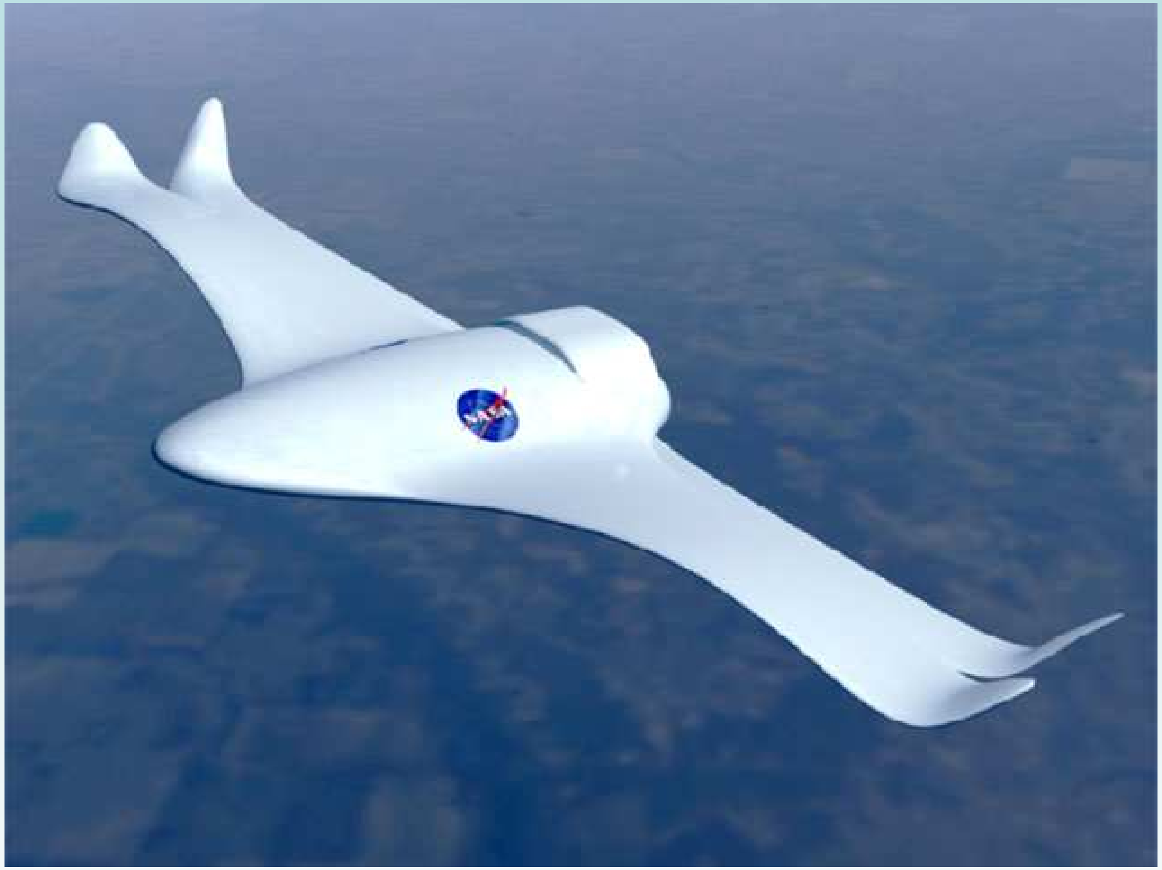
Algorithm	Type of change in signal per Interpolation round		
	Different Increase (up to 4%)	*4% Increase*	*1% Scaling*
Basic Algorithm	9.23	15.82	7.10
Algorithm 1A	9.75	10.96	7.91
Algorithm 2	8.49	10.36	7.94

- K=20

Algorithm	Type of change in signal per Interpolation round		
	Different Increase (up to 4%)	*4% Increase*	*1% Scaling*
Basic Algorithm	18.23	38.78	4.75
Algorithm 1A	6.19	8.99	4.96
Algorithm 2	5.70	9.01	4.74

Conclusion

- A data aquisition algorithm is proposed for a **dense** network of sensor nodes in a **dynamic** environment which is:
  - Distributed
  - Simple
  - Fast
  - Able to track the changes in the signal
    - Average error is non increasing with respect to time



Questions?