Energy Efficient System Partitioning for Distributed Wireless Sensor Networks

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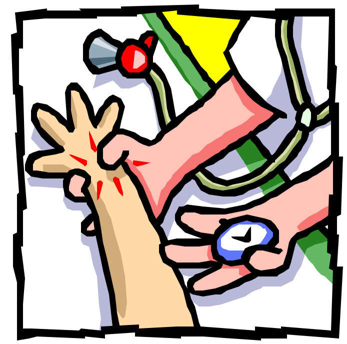
Sensor Network Applications

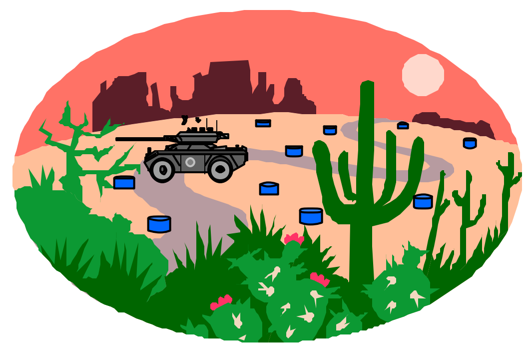
Indoor Home Sensing

Medical Monitoring



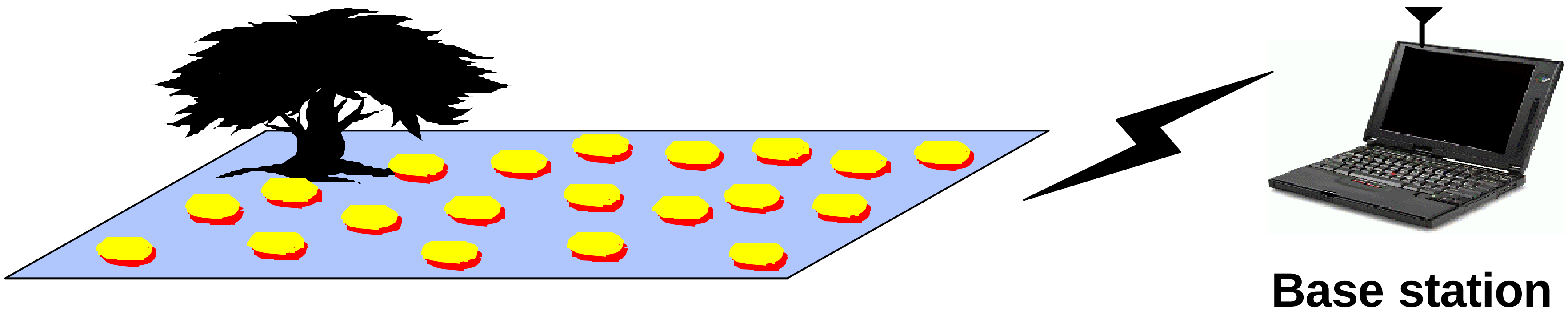
Equipment Monitoring

Vehicle Tracking



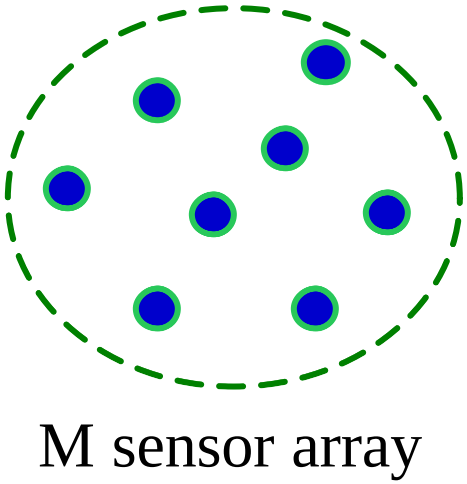
Design and implement energy-efficient data gathering applications for distributed wireless sensors

Domain Characteristics

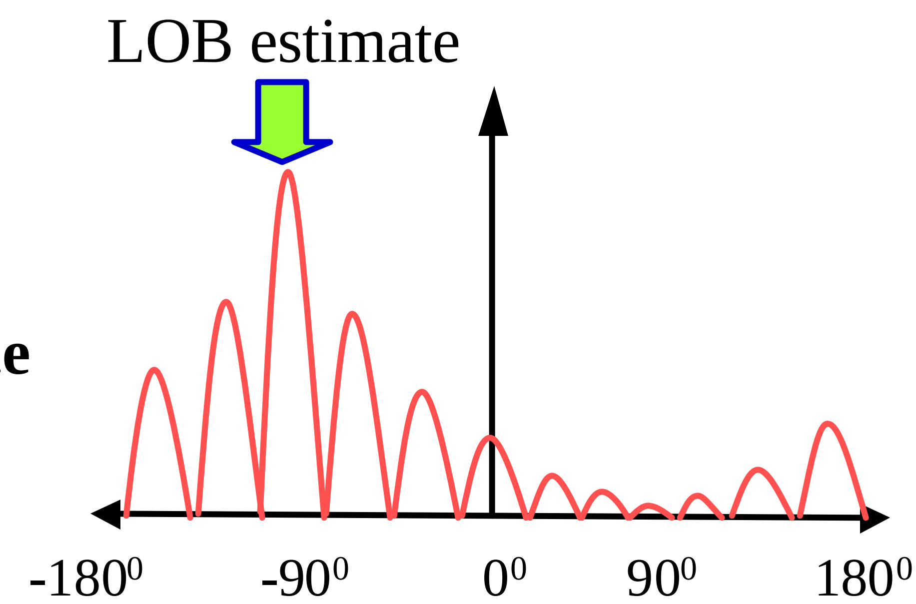


- Lots of static nodes
- Compact form factor
  - 1 cm^3
- Deployed in high densities
  - 0.1 to 20 nodes/m^2
- Low rate sensing
  - < 10 kbps
- Short links between sensors
  - 5 to 10 m
- Sensors far from base station
  - > 100 m
- Long lifetime
  - 1 to 5 years
- Battery replacement impossible

Line of Bearing algorithm (LOB)

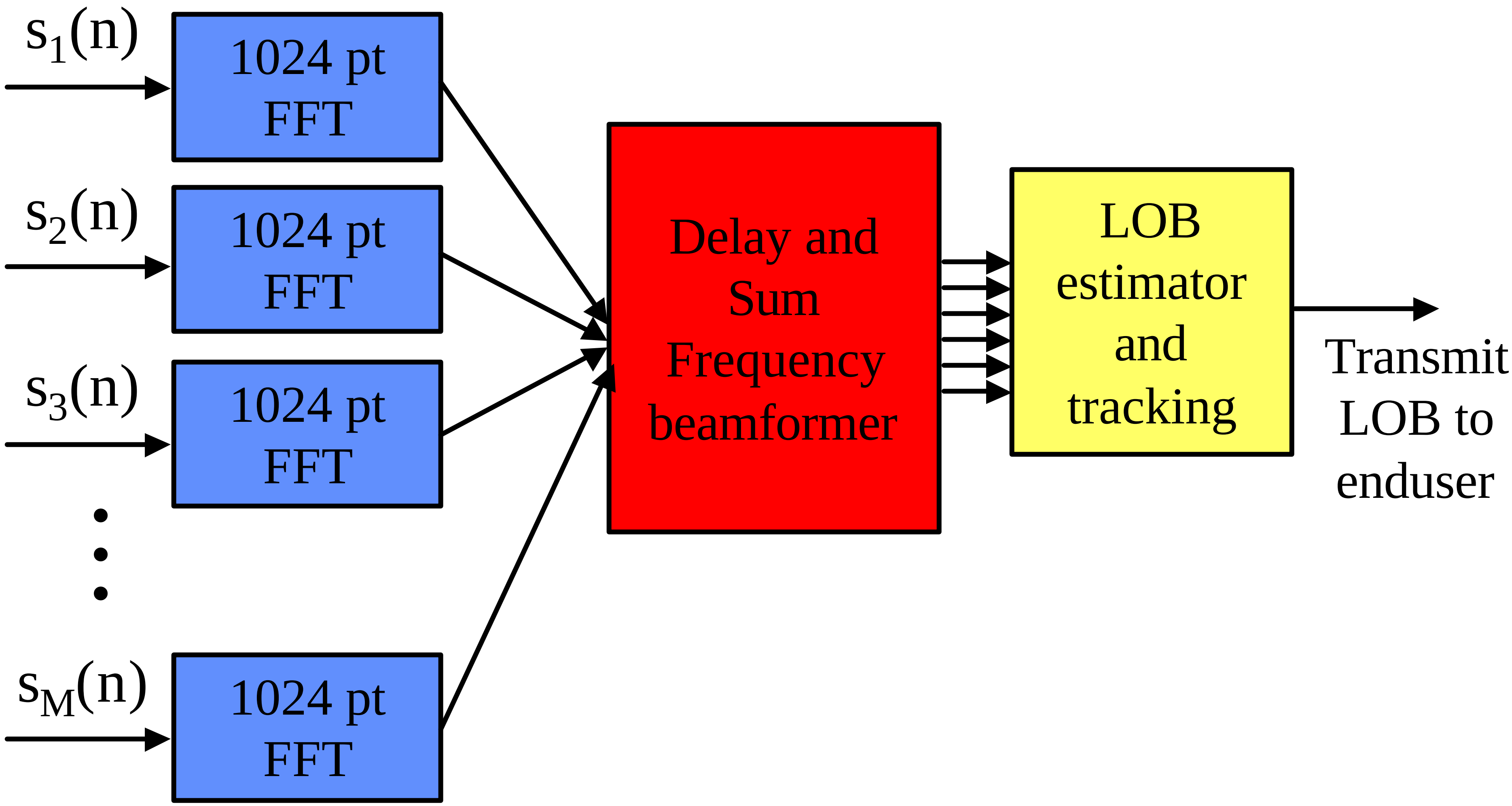


- **Within each sensor cluster use delay-and-sum beamforming to scan in 12 different directions**



- **Direction with most signal energy is the LOB of the source**

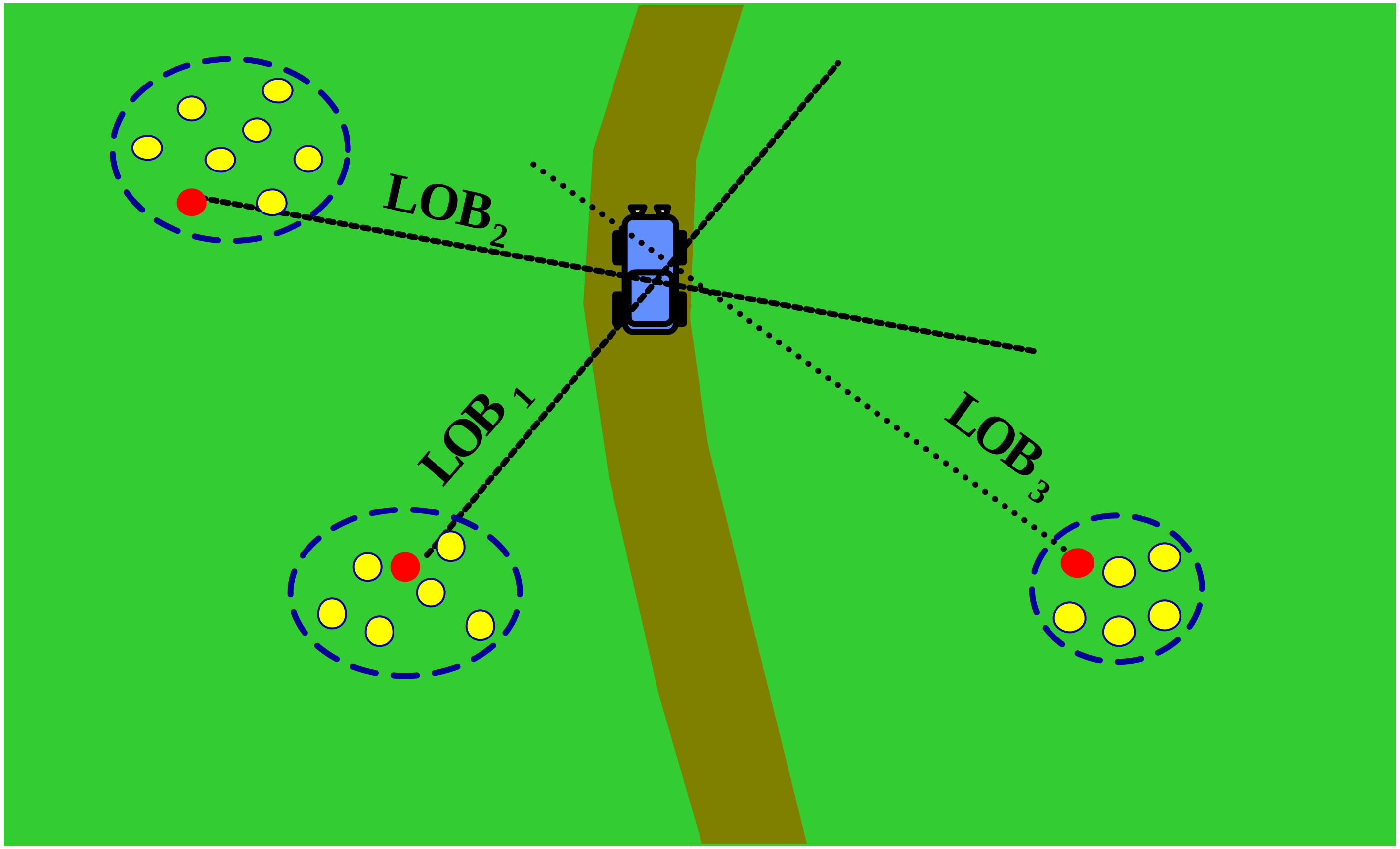
Frequency Domain LOB



- **Delay-and-sum beamforming is done in the frequency domain.**
- **LOB estimator finds the directions with the largest signal energy.**

[courtesy of N. Srour at Army Research Laboratories]

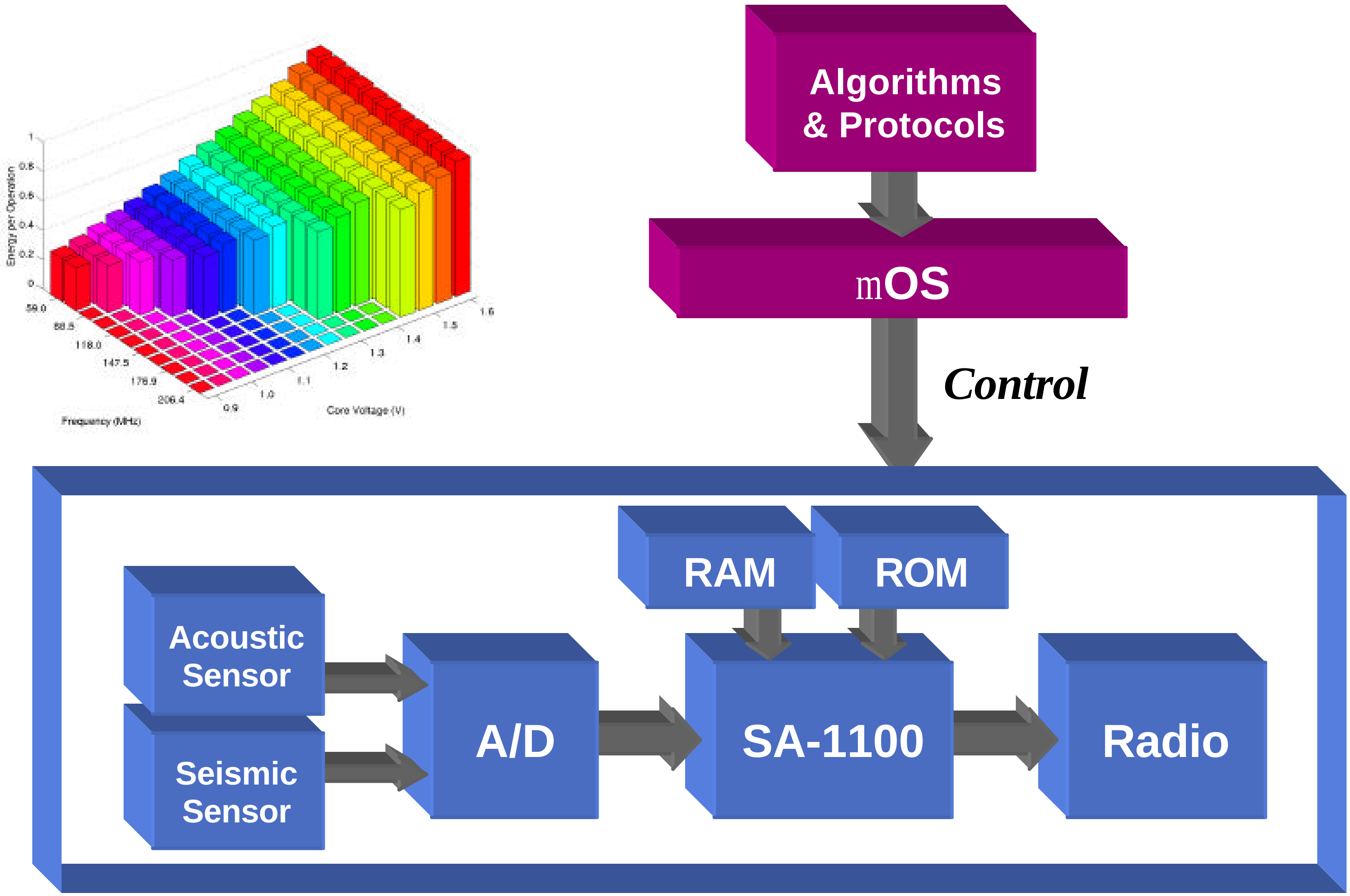
Tracking



- Perform LOB estimation locally within a cluster at “cluster-head”
- Each cluster sends LOB estimate to the end-user where tracking is done
- Trade-off between local computation energy and communication energy

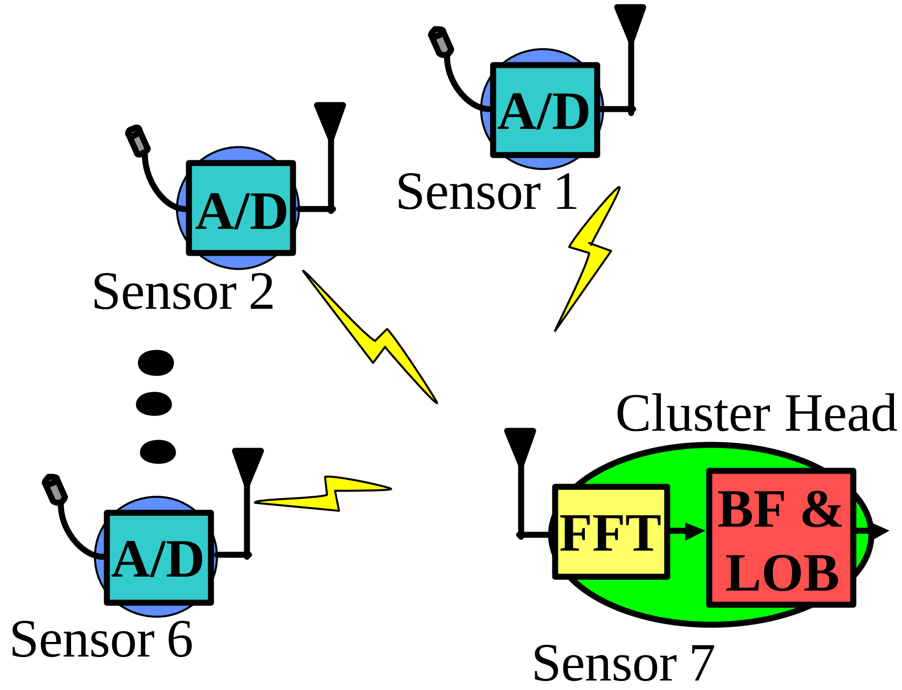
Goal : Develop Low Power algorithms to be run locally at the sensor node

mAMPS Sensor Node



- **LOB estimation will be implemented in software and run on the StrongARM SA-1100 low power processor**
- **StrongARM based node will support various application domains.**

LOB estimation : Direct approach

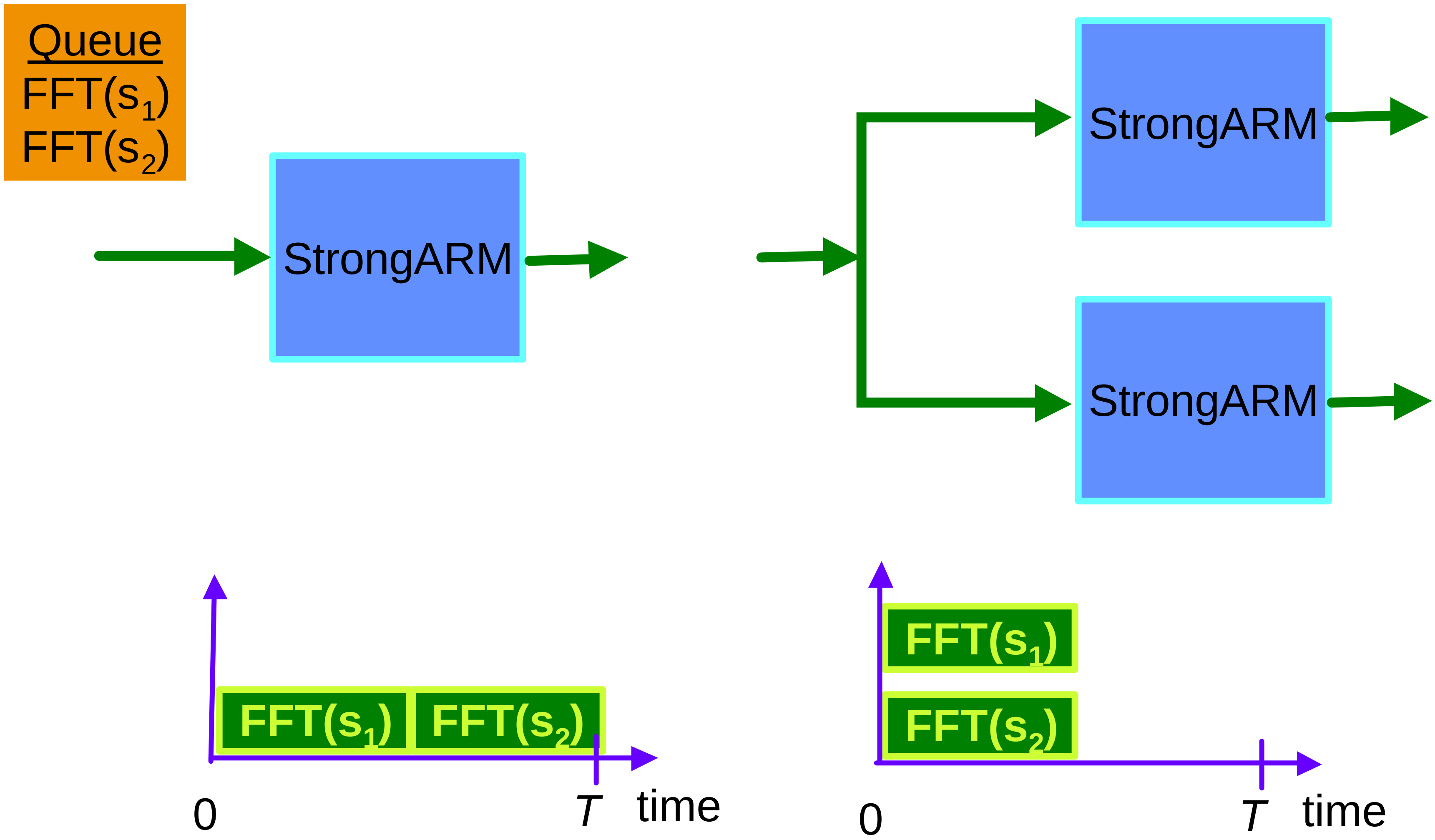


- **Direct approach : All sensors transmit data to the "Cluster head" where LOB estimation is performed.**

$$E_{comp}(V_{dd}=1.44V) = 7 * E_{fft} + E_{bf} + E_{LOB}$$
$$= 6.01 \text{ mJ}$$

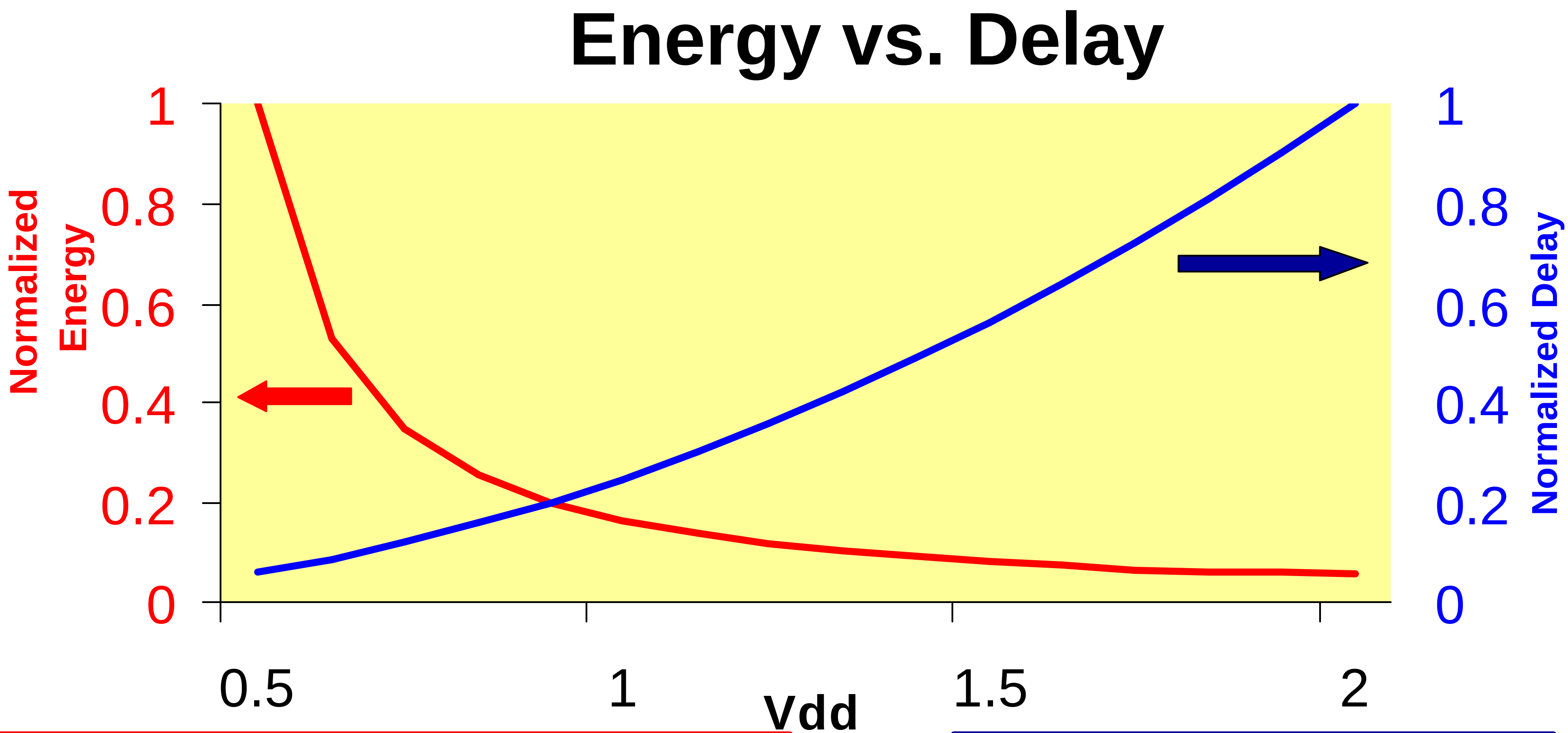
$$Latency_{comp} = 19.2 \text{ msec}$$

Parallelism



$$E_{fft} = 2\, N_{fft}\, C\, V_{fft}^2$$

Energy-Delay Trade-off

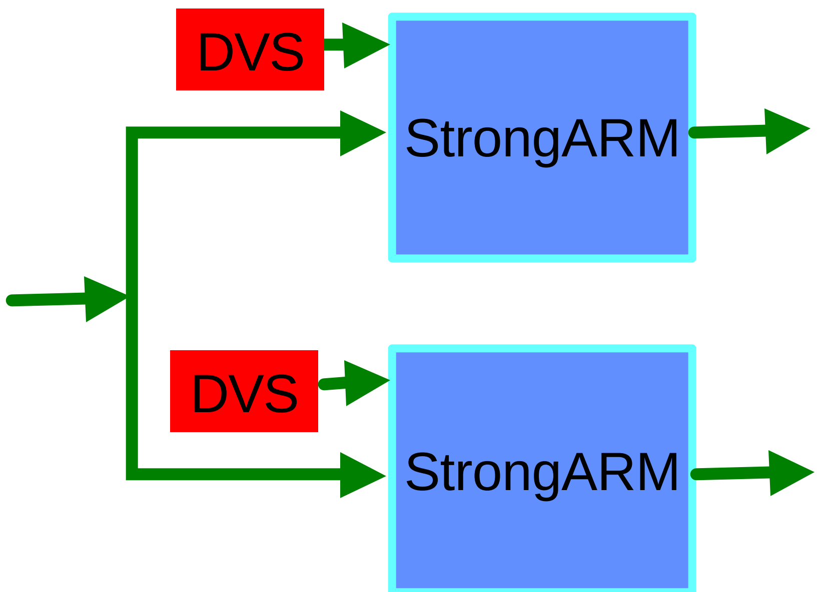


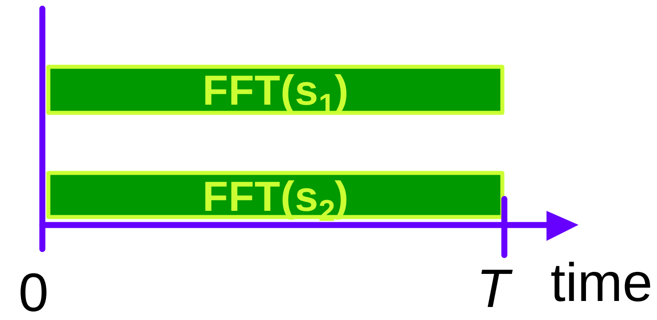
$$E_{computation} = N \cdot C_{switched} \cdot V_{dd}^2$$

$$t_{pd} \geq \frac{V_{dd}}{K(V_{dd} - V_{th})^a}$$

- **Reducing operating voltage means increasing allowable delay (decreasing clock frequency).**

Dynamic Voltage/Frequency



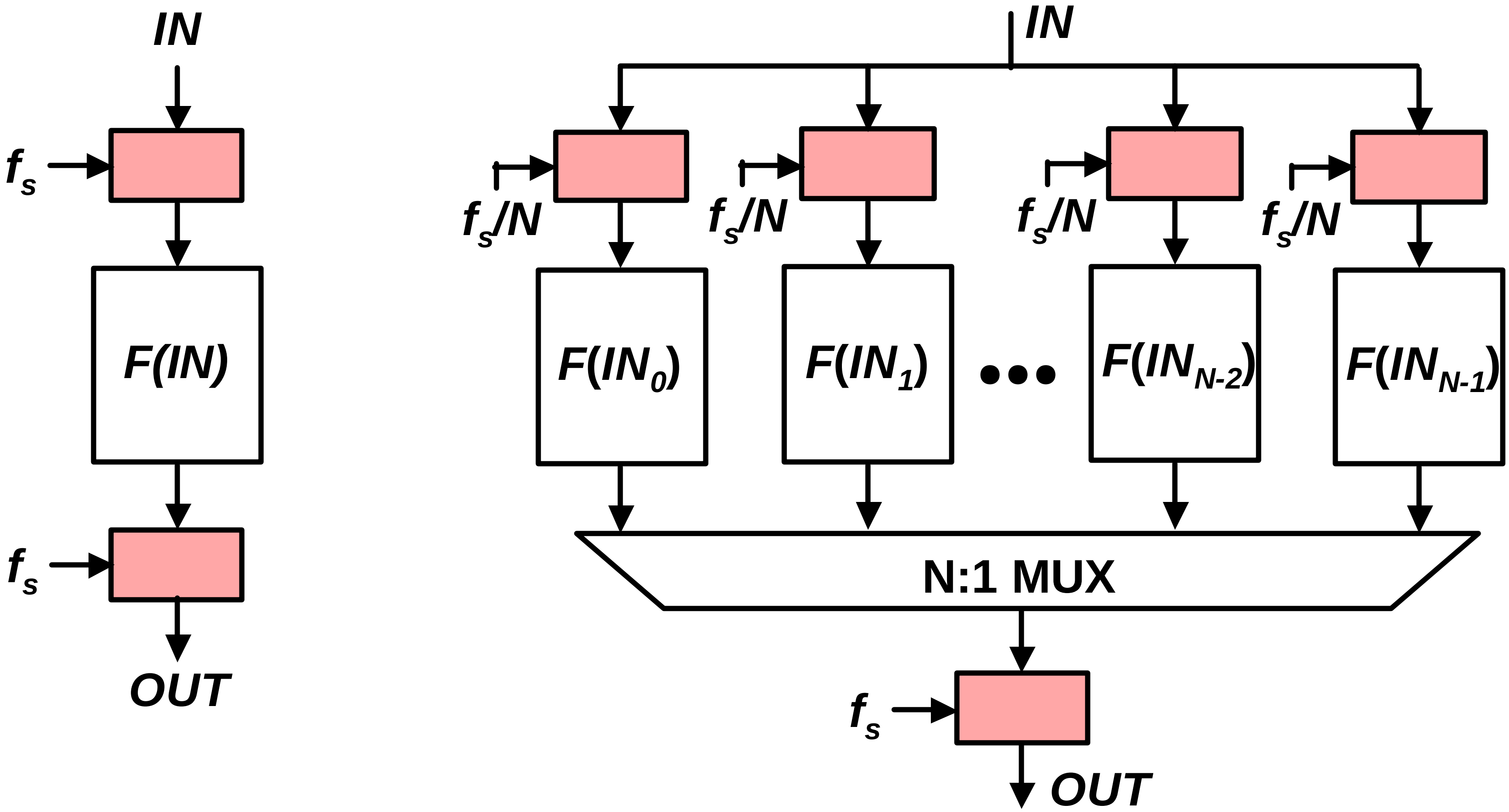


$$E_{fft} = 2\ N_{fft}\ C\ (V_{fft}/2)^2$$

¼ energy dissipated

- **Finding the optimal voltage-frequency for minimum energy dissipation is easy for this example.**
- **Becomes difficult to find optimal voltage-frequency operating points when scheduling multiple tasks (e.g. FFT and beamforming)**

Concurrency Driven Voltage Scaling



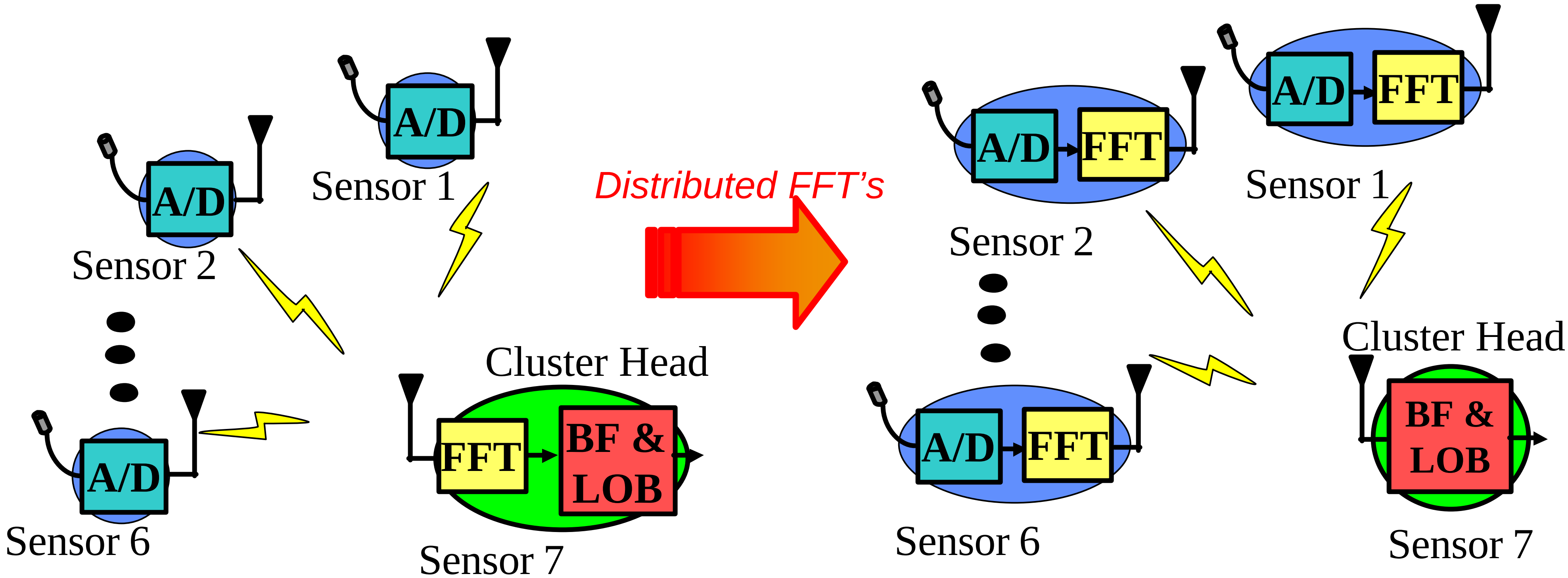
$P_{serial} = C\, V_{ref}^2\, f_s$ $\qquad$ $P_{parallel} = (NC\, V_N^2\, f_s/N) + P_{overhead}$

- Clock rate reduction enables voltage scaling ($V_N < V_{ref}$)

Trade Area for Lower Power

[Chandrakasan92]

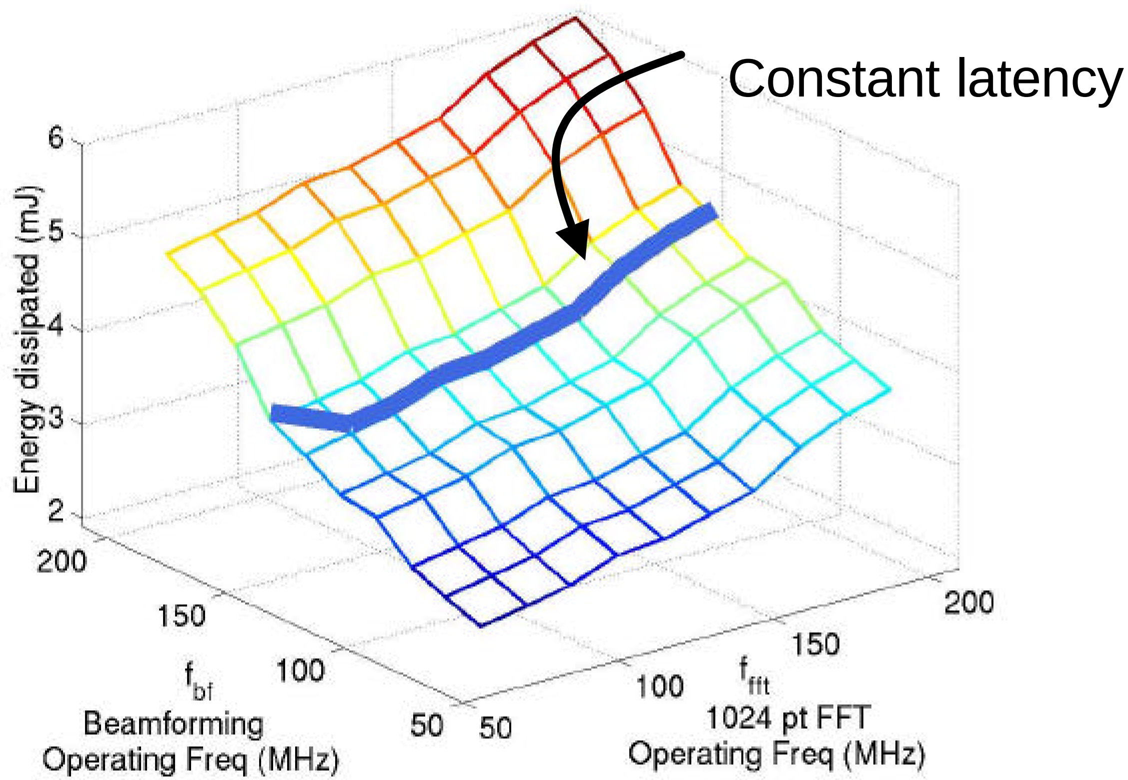
Distributed Processing Exploiting DVS



- **Distributed Technique: FFT is done at node and transmitted to Cluster-head.**

		Direct	Distributed
Nodes	*Vdd*	-	0.85
	f	-	74 MHz
Clusterhead	*Vdd*	1.44 V	1.17 V
	f	206 MHz	162 MHz
	Latency	19.2 msec	18.4 msec
	Energy	6.2 mJ	3.4 mJ

Optimal Voltage-Frequency Scheduling



- **For fixed latency, the optimal voltage-frequency gives the minimum energy dissipated for a given latency constraint.**
- **A closed expression for optimal voltage and frequency is necessary.**

Energy and Delay models

$$E_{comp} = MN_{fft} CV_{fft}^2 + N_{bf} CV_{bf}^2$$

$$T_{comp} \geq t_{fft} + t_{bf} = \frac{N_{fft}}{f_{fft}} + \frac{N_{bf}}{f_{bf}}$$

- **To find the optimal voltage and frequency, minimize E_{comp} given the constraint on latency (Lagrangian minimization problem)**
- **Use the processor delay model to relate voltage and frequency.**

$$f \leq \frac{K(V_{dd} - V_{th})^a}{V_{dd}} \approx K(V_{dd} - c)$$

For the StrongARM processor
K=239.28MHz/V
C=0.5V

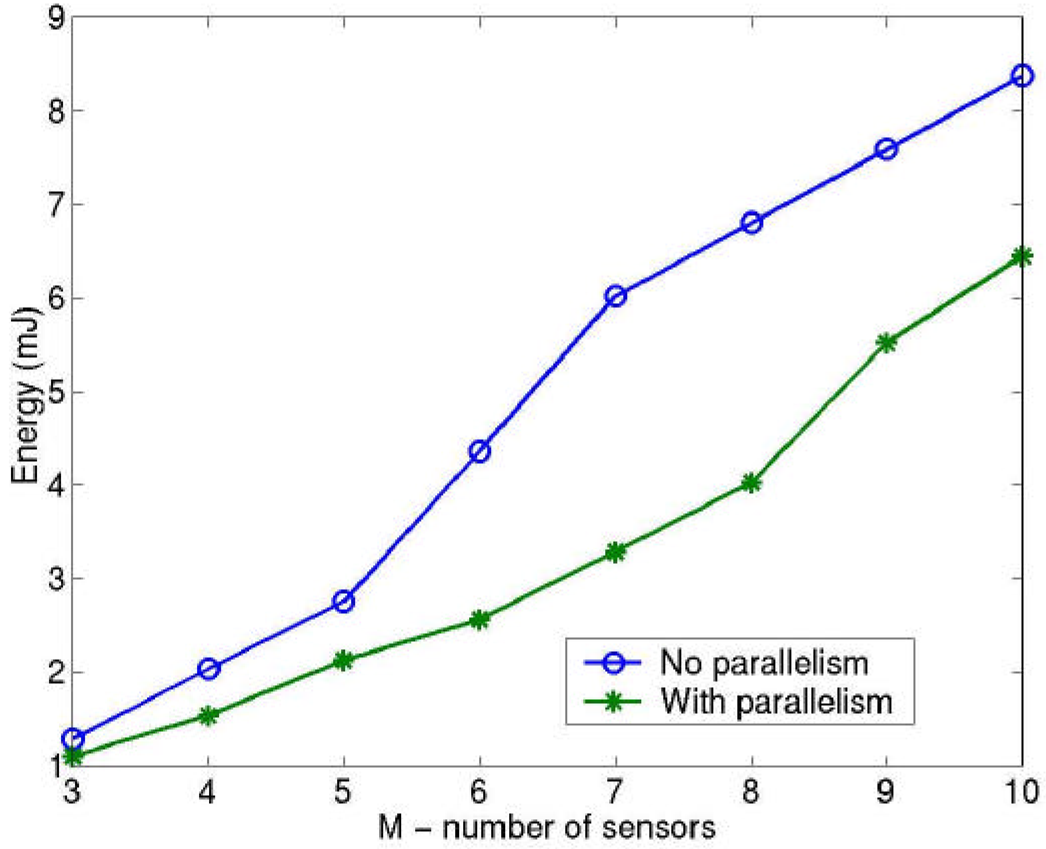
Optimal voltage and frequency scheduling

$$V_{fft} \geq \frac{1}{T_{comp}K}\left[N_{fft} + \frac{N_{bf}}{\sqrt[3]{M}}\right] + c \qquad f_{fft} \leq \frac{\sqrt[3]{M}\,N_{fft} + N_{bf}}{\sqrt[3]{M}\,T_{comp}}$$

$$V_{bf} \geq \frac{\sqrt[3]{M}}{T_{comp}K}\left[N_{fft} + \frac{N_{bf}}{\sqrt[3]{M}}\right] + c \qquad f_{bf} \leq \frac{\sqrt[3]{M}\,N_{fft} + N_{bf}}{T_{comp}}$$

- **Closed form solution for FFT and beamforming voltage and frequency as a function of M, N_{fft} and N_{bf}.**
- **Useful in voltage-frequency scheduling of computation distributed across the network.**

Results



- **As the number of sensors (M) increases, the advantages of using parallelism improves.**

Conclusions

- Partitioning of computation across the network can yield large energy savings.
- A method of finding the optimal voltage and frequency operating points is introduced.
- Using measurements from the StrongARM SA-1100 this technique is verified for a source tracking algorithm using LOB estimation.