Energy Efficient Protocols for Low Duty Cycle Wireless Sensor Networks

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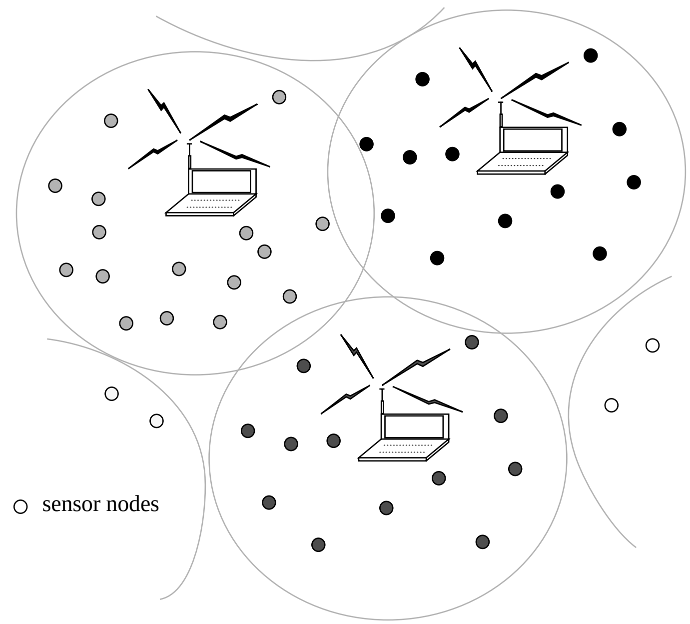
Environment Monitoring Sensor Network

Application Scenario : Factory machine monitoring

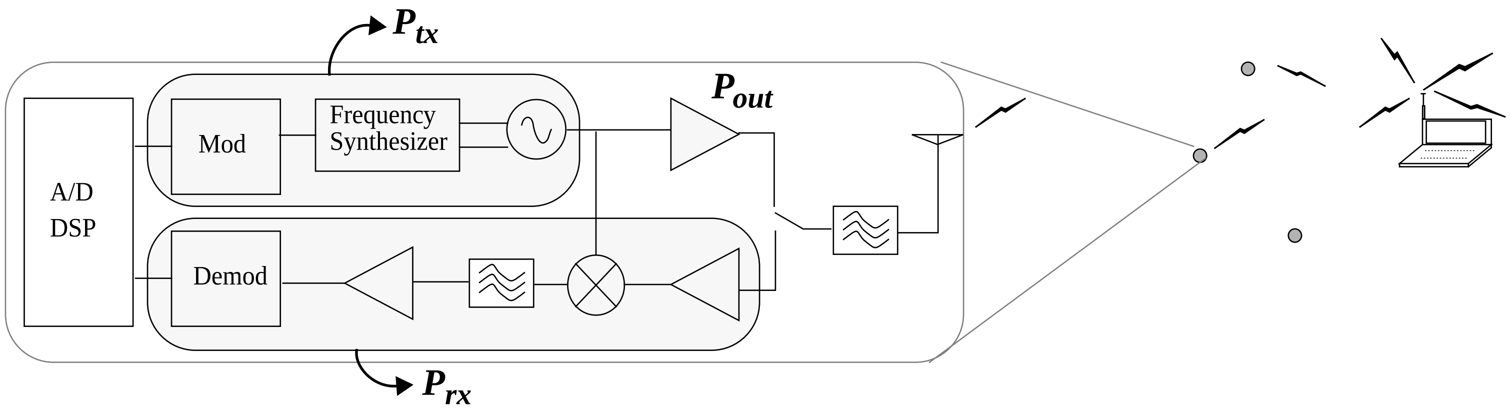
Cell density	< 300 in 5m x 5m < 3000 in 100m x 100m
Range of link	< 10 meters
Packet rate (packet = 2 bytes)	average : 20 packets/sec max : 100 packets/ sec min : 2 packets/sec
Packet Error Rate	$< 10^{-6}$ after 5ms $< 10^{-9}$ after 10ms $< 10^{-12}$ after 15ms
Frequency	5.725~5.875GHz ISM

<courtesey of ABB research>



❑ **Minimize the energy consumption of the sensors by efficient protocols based on energy models extracted from physical layer electronics**

Sensor Node

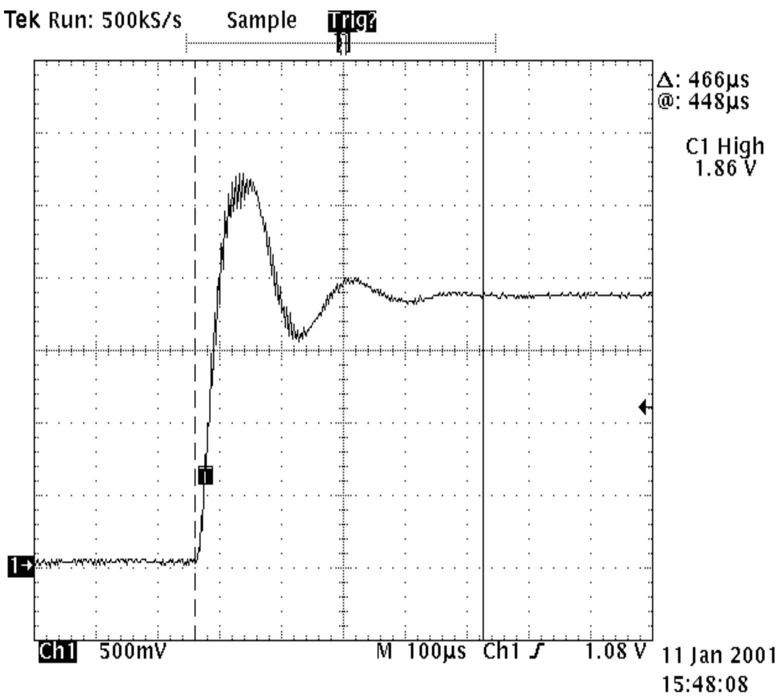


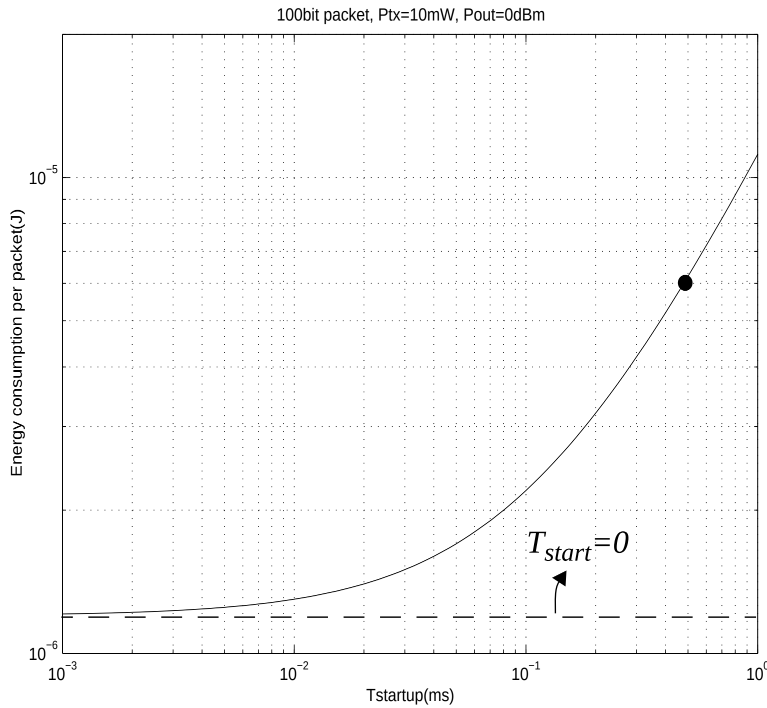
$$Average\ Power = N_{tx\text{-}avg}\{P_{tx}\ (T_{transmit} + T_{start}) + P_{out}\, T_{transmit}\}$$
$$+ N_{rx\text{-}avg}\, P_{rx}\,(T_{receive} + T_{start})$$

- $P_{rx/tx}$ dominates over P_{out} (<< 0dBm) due to short distance

- Startup cost significant portion of overall power

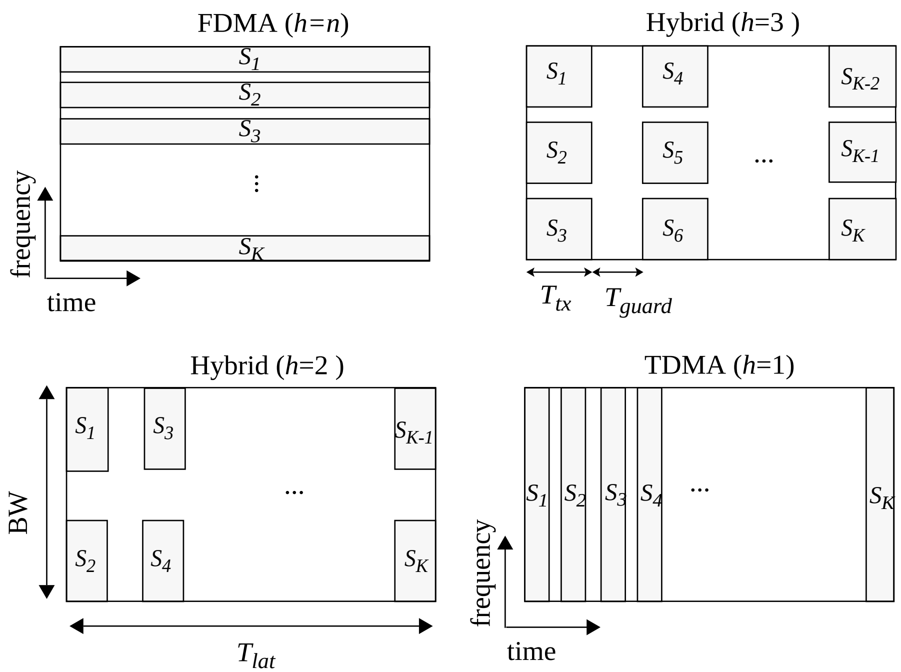
Effect of Startup Transient





❑ **Startup energy must be taken into account in protocol design**

Low Power MAC



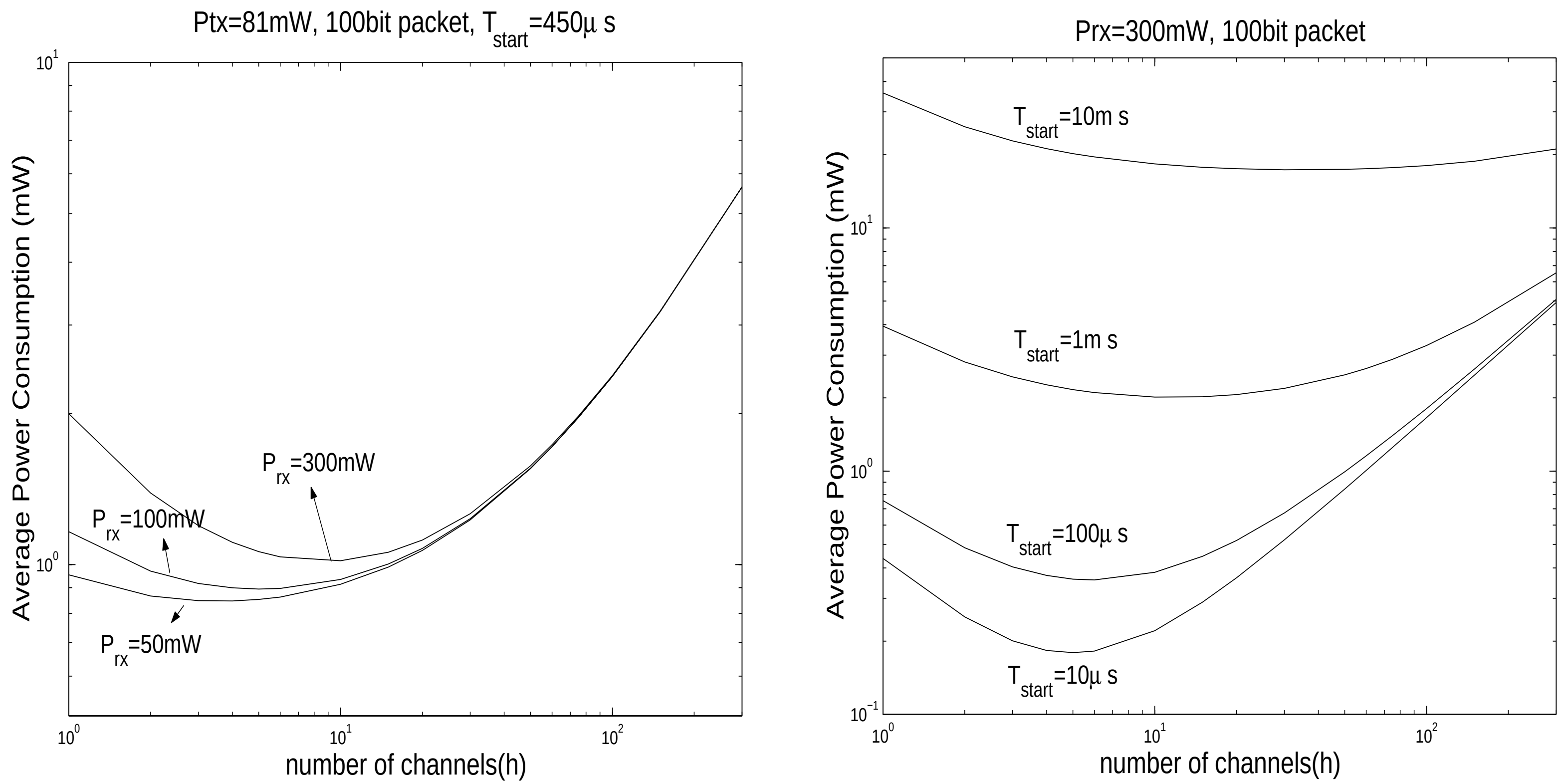
$$T_{collision} = T_{guard} / \delta$$

$$\boldsymbol{N_{rx}} = \frac{\delta}{\boldsymbol{T_{guard}}}$$

$$P_{avg} = N_{tx} \cdot (P_{tx} \cdot (T_{transmit} + T_{start}) + P_{out} \cdot T_{transmit})$$
$$+ N_{rx} \cdot P_{rx} \cdot (T_{receive} + T_{start})$$

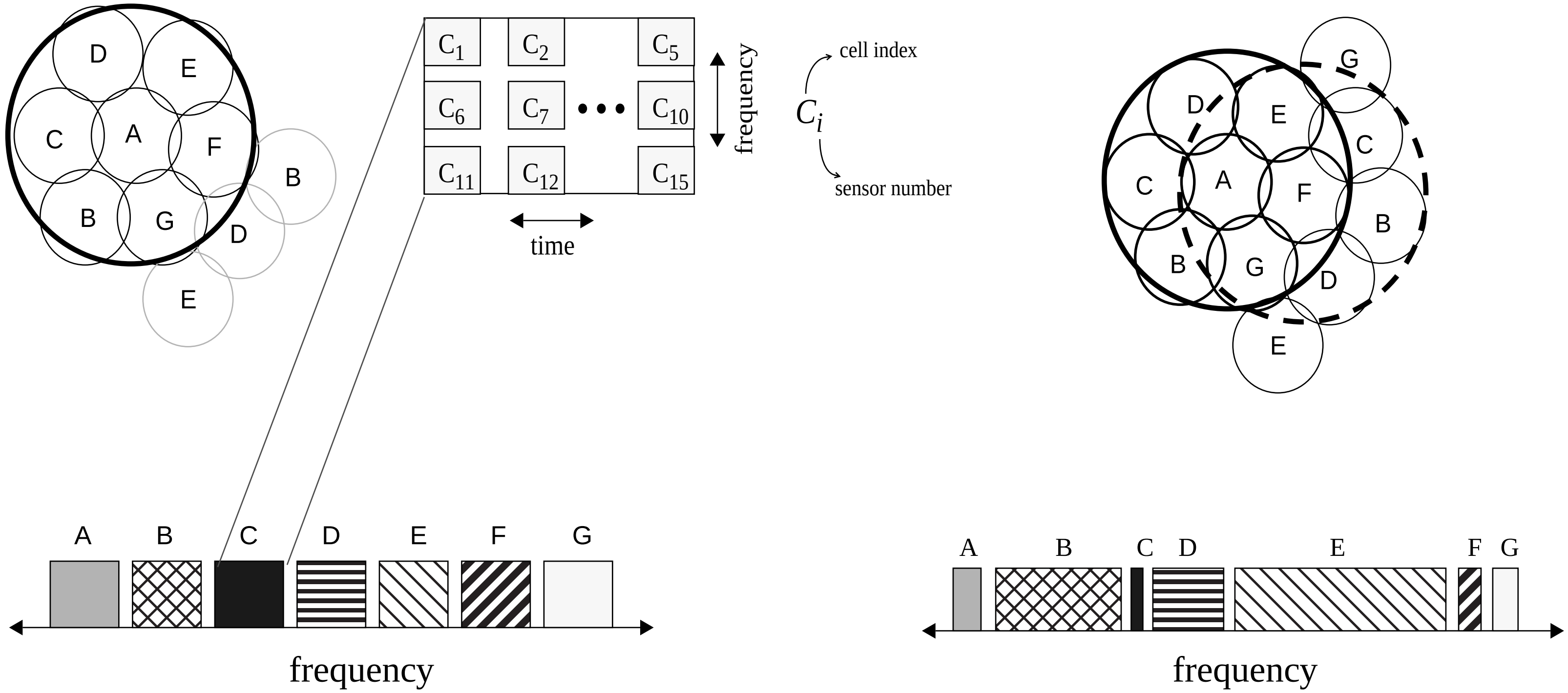
- **Trade off between transmitter and receiver energy consumption**

Hybrid TDM-FDM



❑ **Higher receiver power prefers FDM, lower receiver power prefers TDM**

Variable frequency band allocation

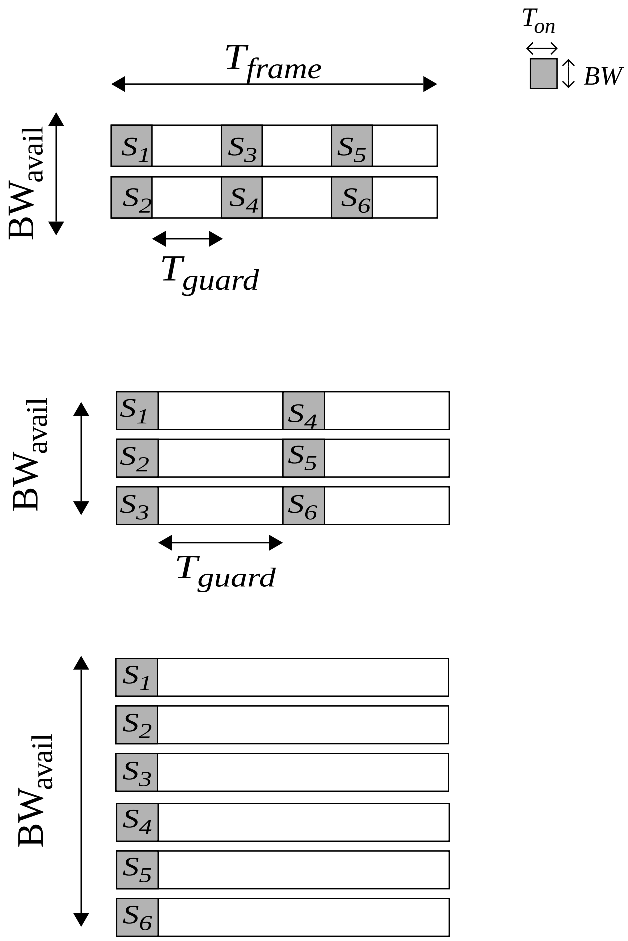


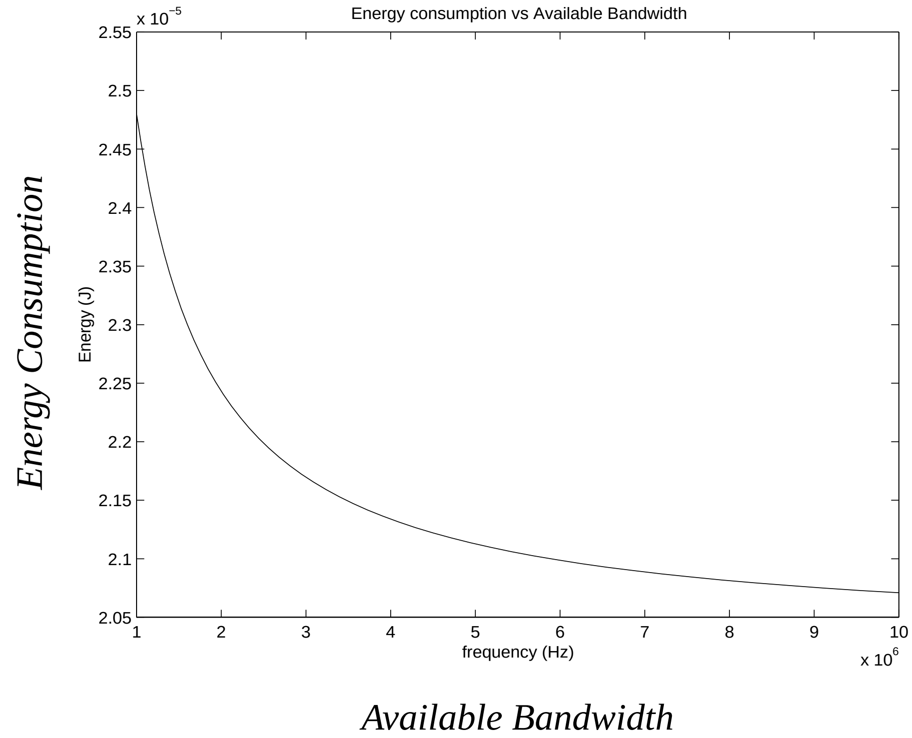
Fixed bandwidth allocation

Variable bandwidth allocation

- ❑ Variable bandwidth allocation allows more average bandwidth per sensor
- ❑ Cochannel interference must be avoided

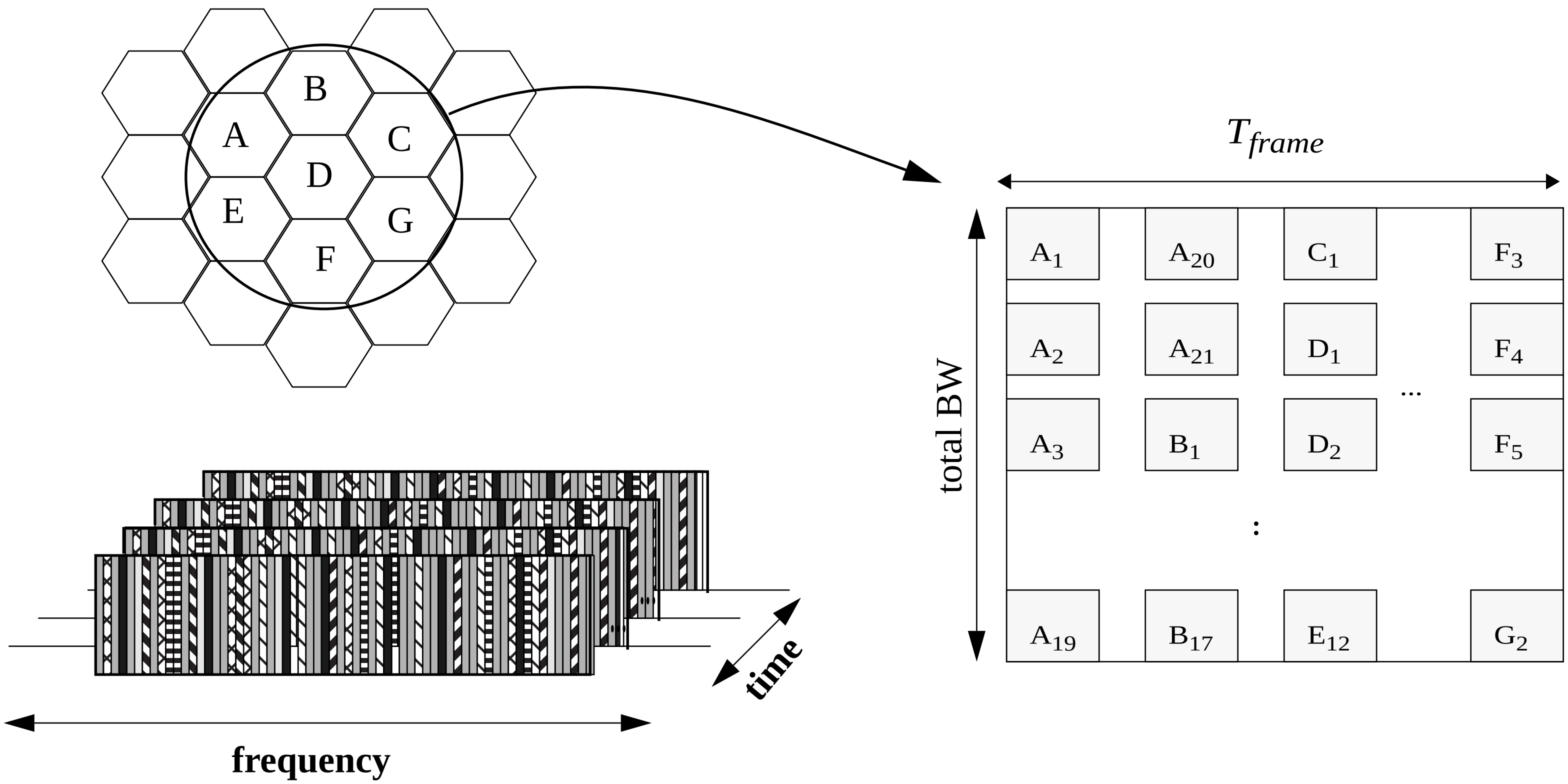
Energy vs Bandwidth





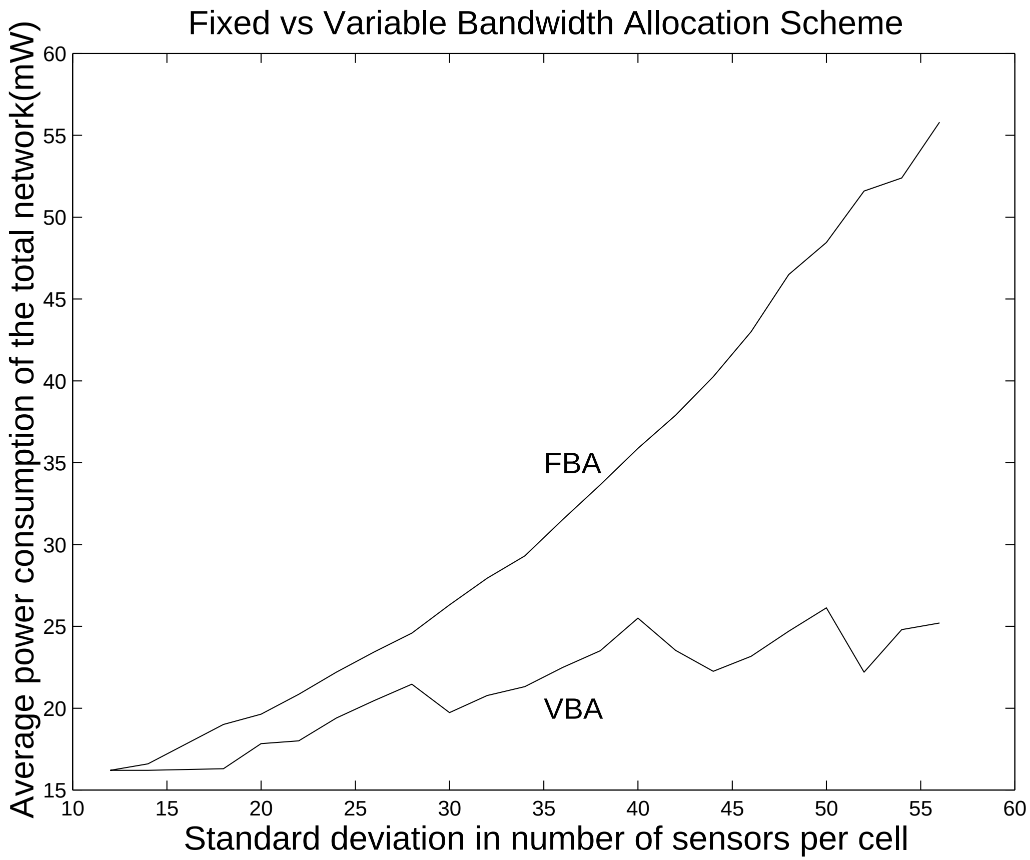
❑ **Large bandwidth allows less synchronization & less energy consumption**

Time Synchronized Intercellular System



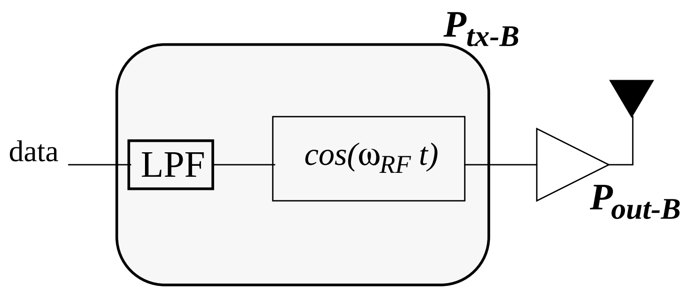
❑ **By maintaining time synchronized network, time-frequency slots can be assigned to sensors such that co-channel interference is avoided**

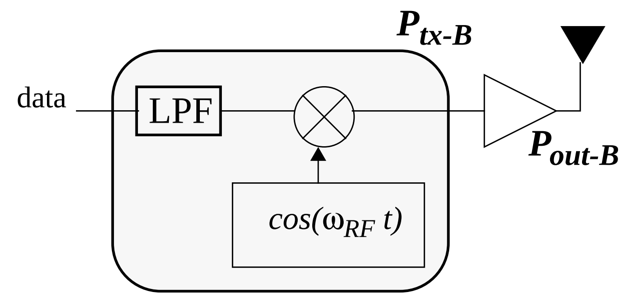
Simulation Result



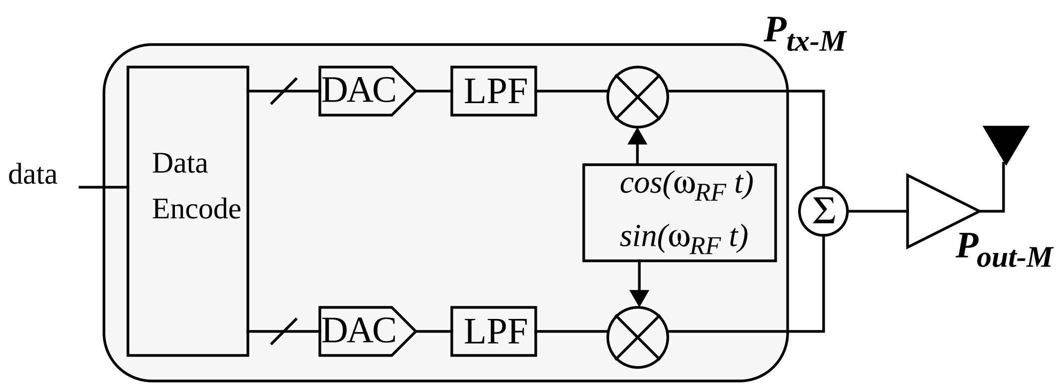
❑ **Variable bandwidth allocation scheme achieves lower energy as the variance in spatial distribution of sensors gets large**

Modulation





$$E_{binary} = P_{tx\text{-}B}\,(T_{on} + T_{start}) + P_{out\text{-}B}\,T_{on}$$



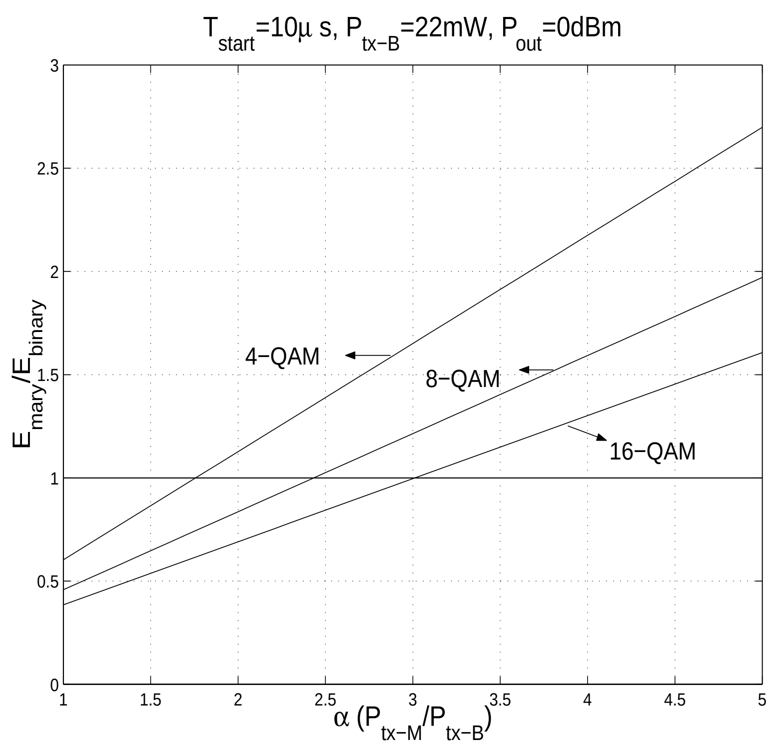
$$E_{M\text{-}ary} = P_{tx\text{-}M}\,(T_{on}/n + T_{start}) + P_{out\text{-}M}\,T_{on}/n$$

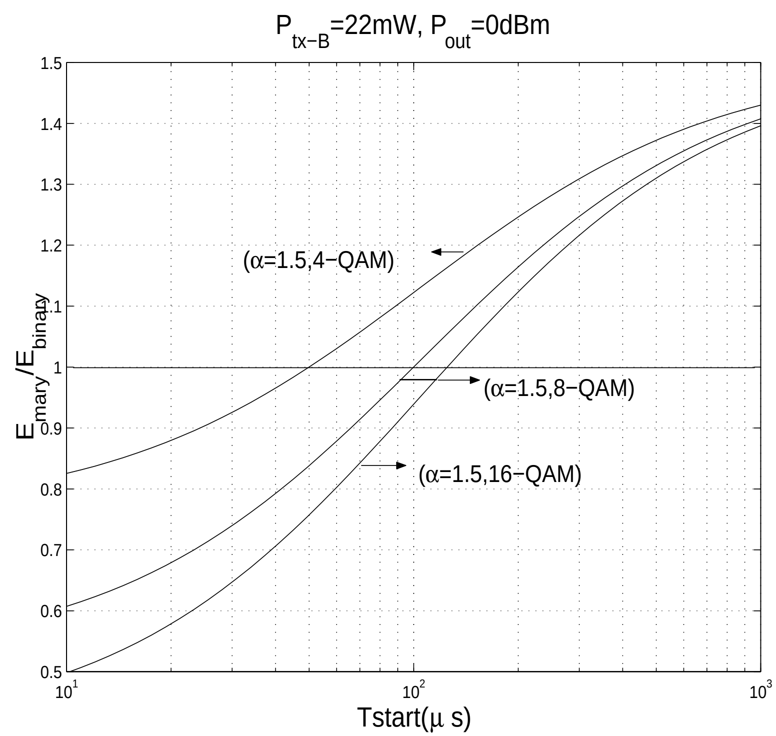
$$= \alpha\, P_{tx\text{-}B}\,(T_{on}/n + T_{start}) + P_{out\text{-}M}\,T_{on}/n$$

$$\alpha = \frac{P_{tx\text{-}M}}{P_{tx\text{-}B}}$$

Energy comparison

$$E_{M\text{-}ary} < E_{binary} \quad \text{if} \qquad \alpha < \frac{P_{tx\text{-}B}\,(T_{on} + T_{start}) + P_{out\text{-}B}T_{on} - P_{out\text{-}M}\,T_{on}/n}{P_B\,(T_{on}/n + T_{start})}$$





- **Worth going to M-ary modulation only if overhead α and T_{start} is small**

Conclusion

- ❑ Low power MAC : hybrid TDM-FDM

  - Trade-off between energy consumption of transmitter and receiver

- ❑ Variable bandwidth allocation scheme

  - Exploit the wide spatial distribution of static sensor network

- ❑ Modulation scheme

  - M-ary more energy efficient if overhead and startup time is small

- ❑ **Design of communication protocols must incorporate non-ideal behaviours of physical layer electronics.**