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Nimbus
Embedded Systems Research

# Energy Aware Communication for Wireless Sensor Networks

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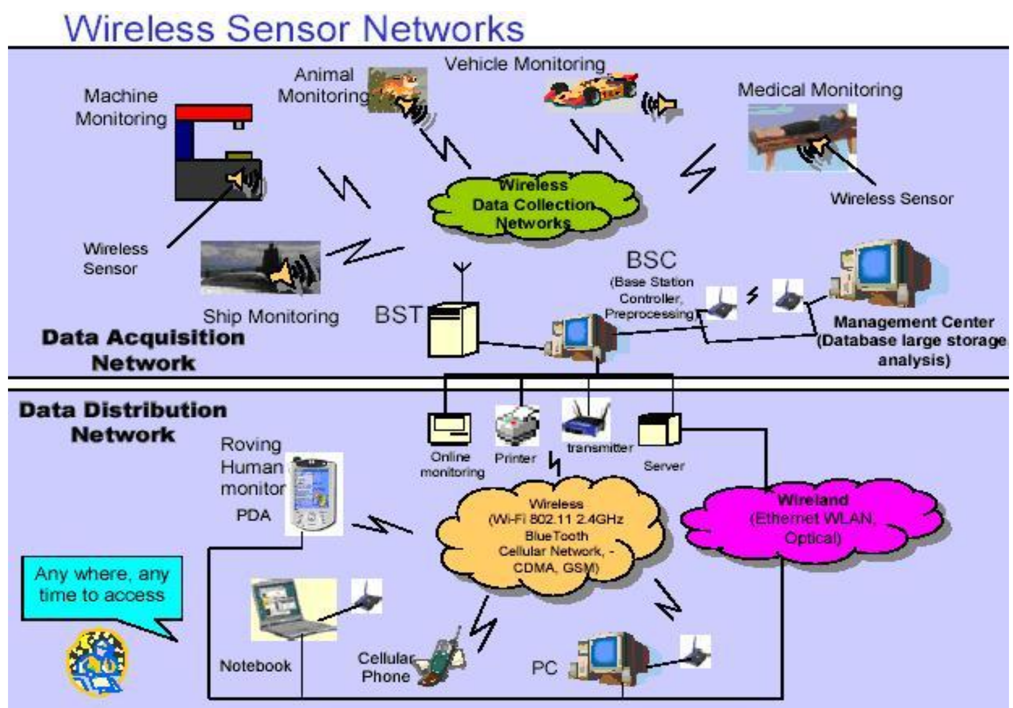
# Wireless Sensor Networks - WSN


Next stage in distributed sensing is combining sensing with actuation and control towards Cyber Physical Systems (CPS) or Networked Embedded Control Systems (NECS)

# Example Application:
# Building Energy Management

**Building sector has:**

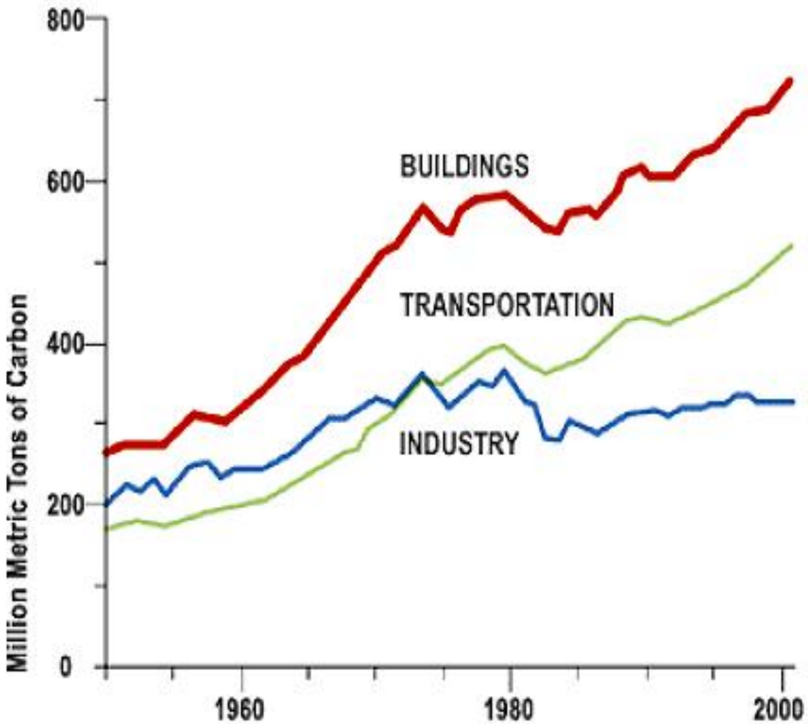
**Largest Energy Use!**

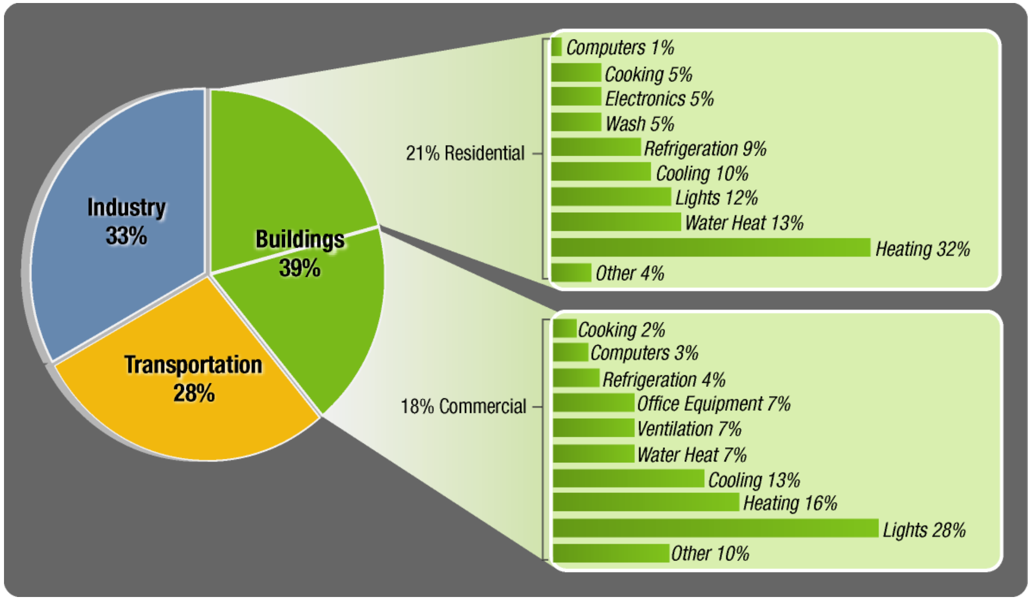
**Fastest growth rate!**

**Buildings consume 40% of total U.S. energy**

- ***71% of electricity***
- ***54% of natural gas***

***No Single End Use Dominates***



# Sensor-Actuator Networks in Building Management

- Energy in buildings accounts for almost half of the total amount of energy consumed in EC
- Fossil fuels the primary energy source, building sector produces 22% of total CO2 emissions - more than produced by the industrial sector
- Almost 85% of the energy is for low temperature applications such as space and water heating
- Retrofit WSAN can contribute to energy reduction

# What are the challenges in WSAN Design?

- Cost effective energy management for long term autonomous operation of large scale WSAN
  - Autonomous, computationally efficient power management
  - Energy harvesting

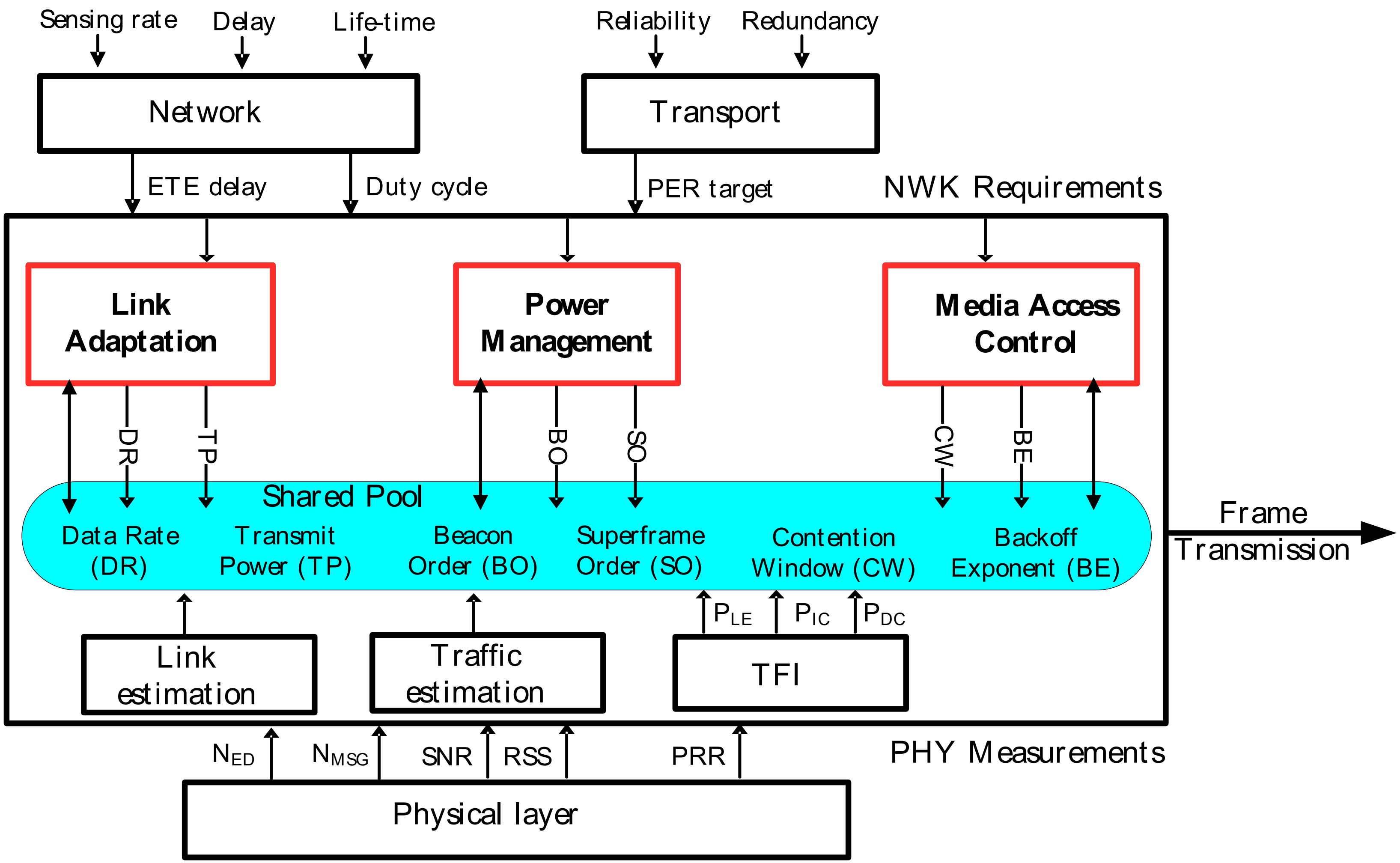
- Design and Deployment support for large WSAN
  - Tools that support design to achieve joint design of
    - wireless network
    - often heterogeneous sensing/actuation requirements
  - Need to estimate lifetime of WSANs prior to deployment

- Reliable wireless communication
  - Co-existence issues in unlicensed radio spectrum
  - Harsh radio environments in many application domains
  - Reliability to support control over wireless

# More Challenges

- Management of QoS and energy expenditure to support control over wireless
  - Current control requires real-time real-time data delivery
  - Future joint design of wireless networks and control applications
- Management and operation of large scale WSAN
  - Need for WSAN to adapt autonomously to environmental changes to minimise power consumption at all times
  - But also desire to manage and diagnose WSAN operation in many critical applications
- Need for WSN design templates to avoid custom design for every application
  - Too often custom designs for each application
  - Templates are required to reduce costs in WSN design

# Example: Energy Management Framework for IEEE802.15.4

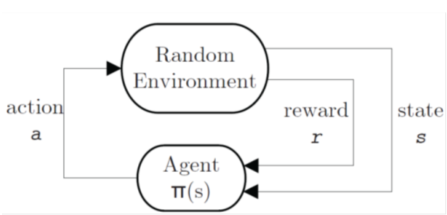


# Duty Cycle Learning (DCLA)

- The DCLA protocol is based on Q-learning
- DCLA explores and selects new actions adaptively according to the rewards received
- DCLA adapts duty cycle in event-based scenarios
- Implemented in OPNET and on telosB motes

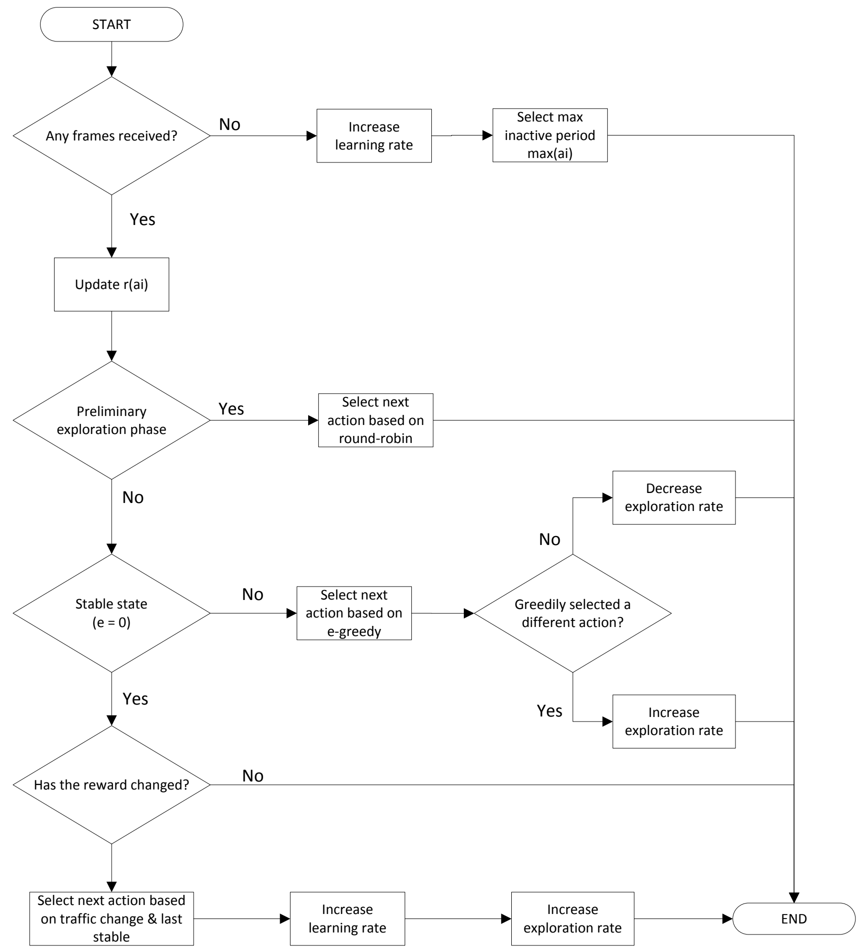
$$Q_{new}(a_i) \longleftarrow Q_{old}(a_i) + \alpha(r(a_i) - Q_{old}(a_i))$$

$$\Pi(a_i) = \begin{cases} rand[Q(a)] & if\ \epsilon > rand() \\ argmax_a[Q(a)] & otherwise \end{cases}$$



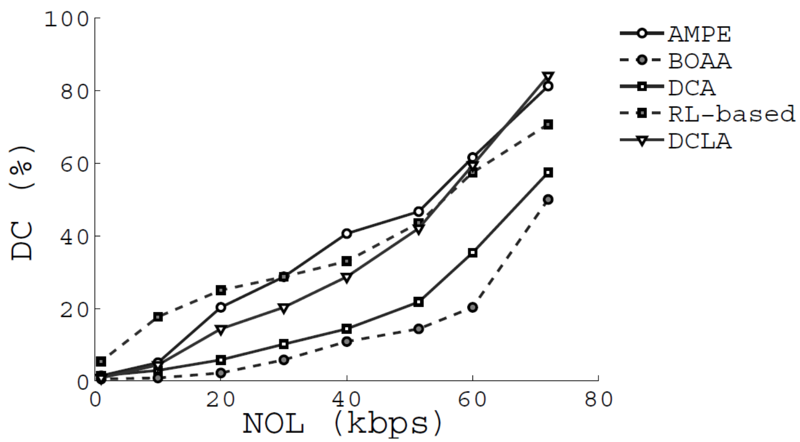

$$r(a_i) = \begin{cases} -O & \text{if } O > O_{max}, \\ -IL - D & \text{if } O < O_{min}, \\ 1 - IL - D & \text{otherwise.} \end{cases}$$

$$a_i = BO - SO \qquad 0 \le i \le k$$

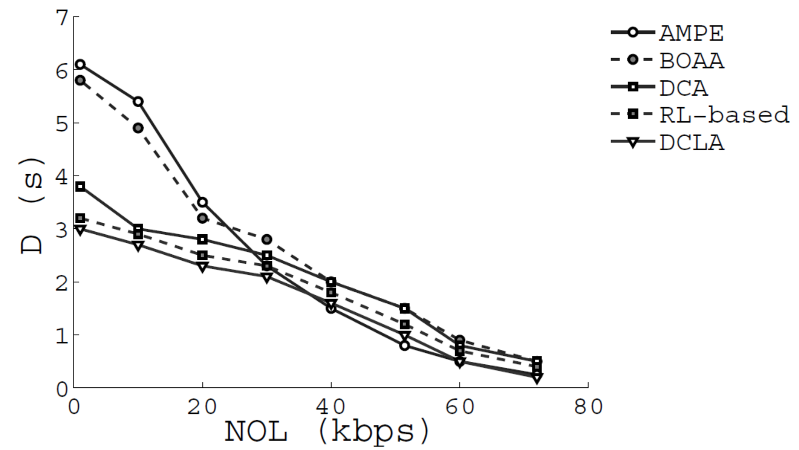



R. de Paz Alberola, D. Pesch, “Duty Cycle Learning Algorithm (DCLA) for IEEE 802.15.4 Beacon-Enabled Wireless Sensor Networks”, Ad-hoc Networks, Elsevier, (http://dx.doi.org/10.1016/j.adhoc.2011.06.006)

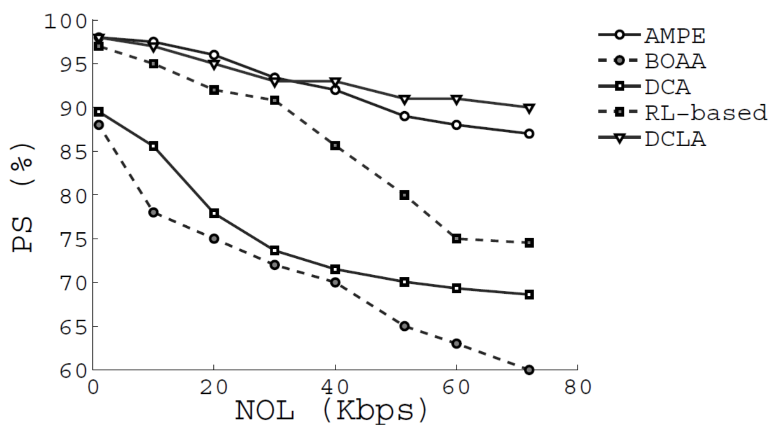
# Periodic Monitoring Application



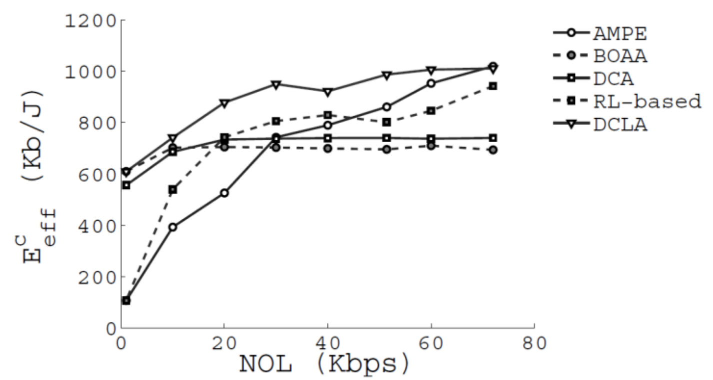

Average Duty Cycle (DC) selection




Average end-to-end delay (D)

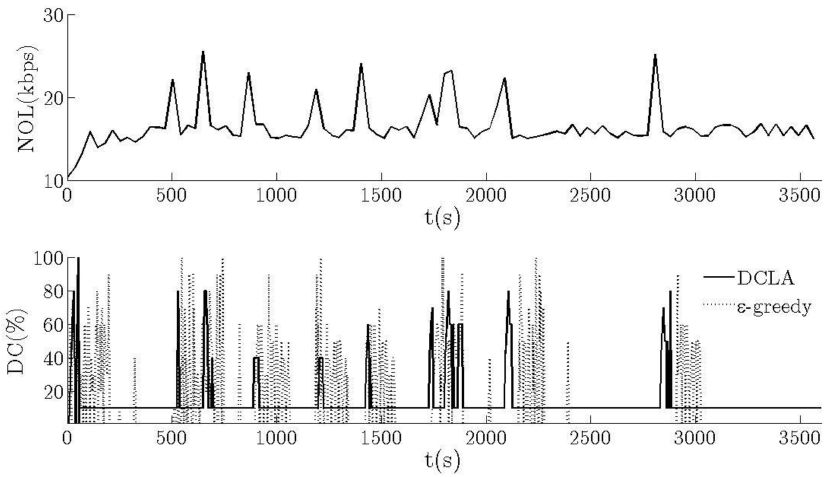



Probability of Success (PS)



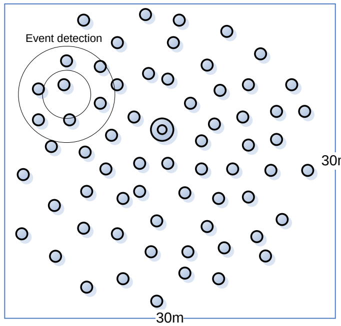

Energy Efficiency

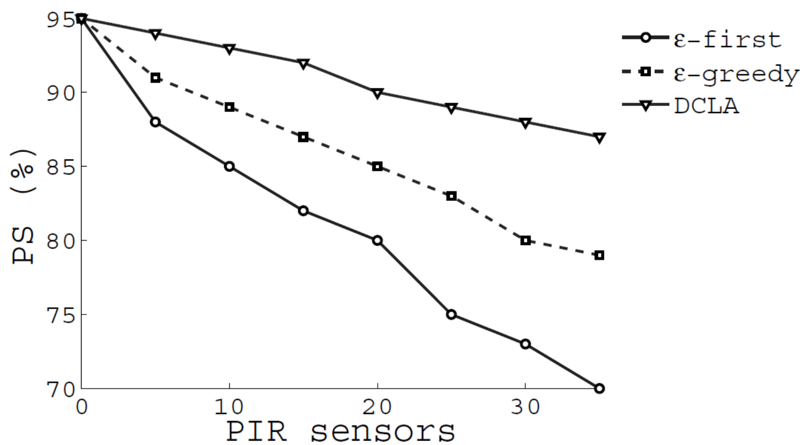
# Event-based Monitoring



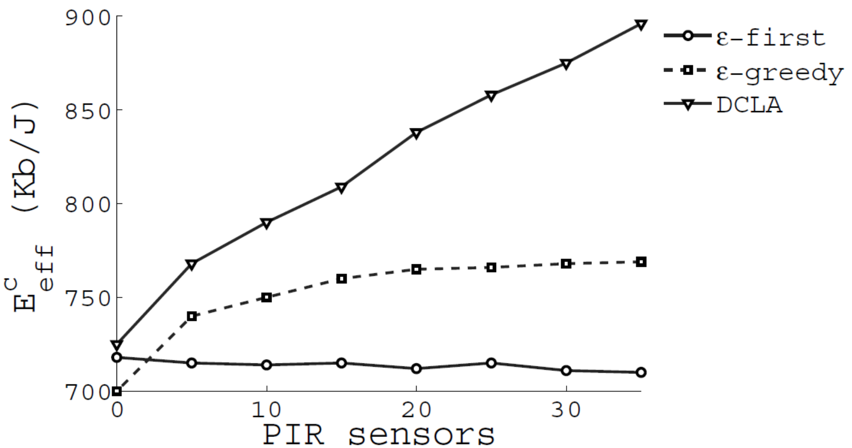

Instantaneous DC selection

- PIR sensors detect event and report to the sink
- Other nodes generate periodic monitoring data



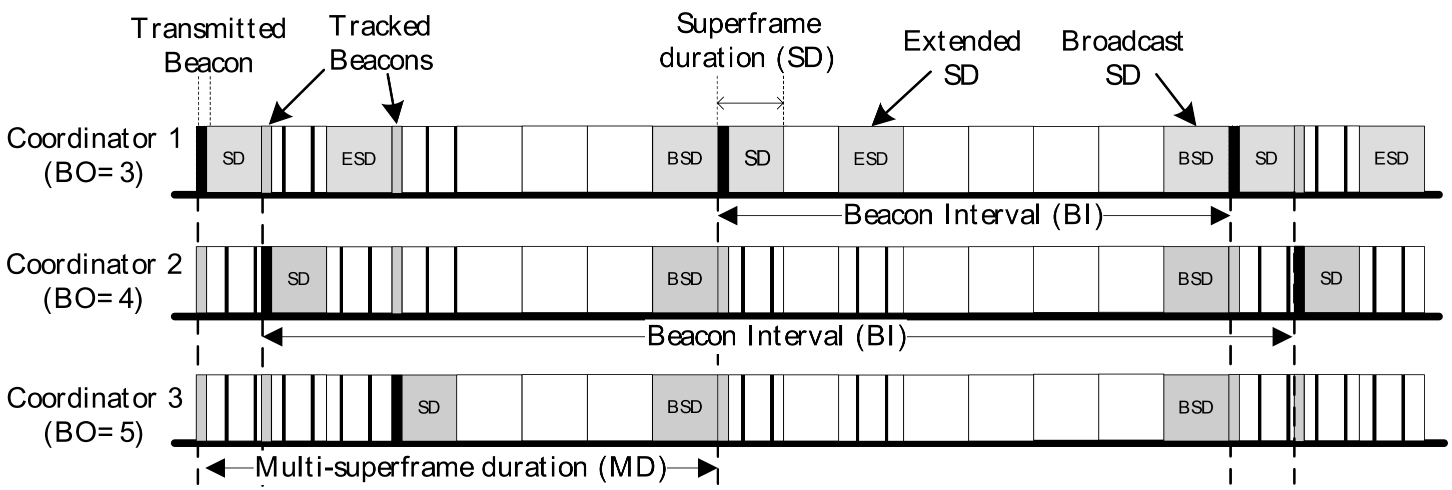

Probability of Success




Energy Efficiency

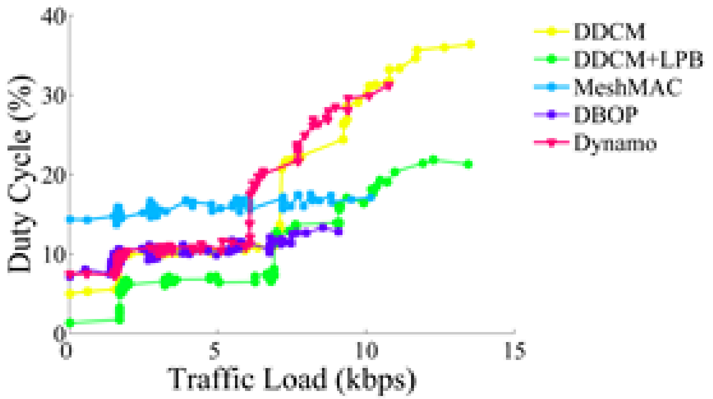
# Distributed Duty Cycle Management (DDCM)

- Distributed Duty Cycle Management (DDCM) for IEEE 802.15.4 Beacon-Enabled Wireless Mesh Sensor Networks.
  - DDCM uses DCLA to adapt a node's duty cycle to the network traffic and manages the allocation of time slots as well as the prevention and resolution of possible slot conflicts within a mesh network

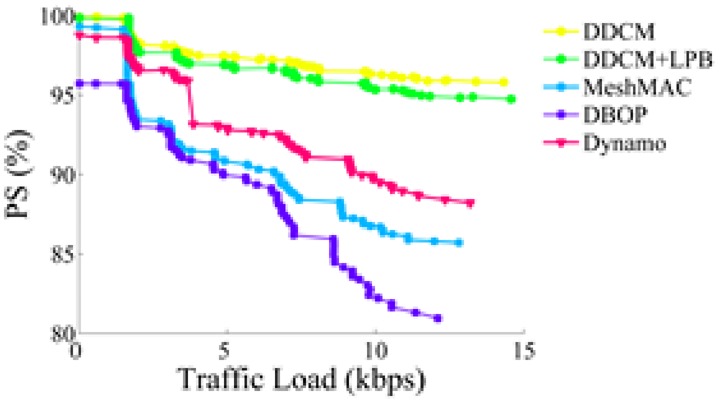



R. de Paz Alberola, B. Carballido Villaverde, D. Pesch, "Distributed Duty Cycle Management (DDCM) for IEEE 802.15.4 Beacon-Enabled Wireless Mesh Sensor Networks", in Proc. of 5th IEEE International Workshop on Enabling Technologies and Standards for Wireless Mesh Networking, Valencia, Spain, October 2011

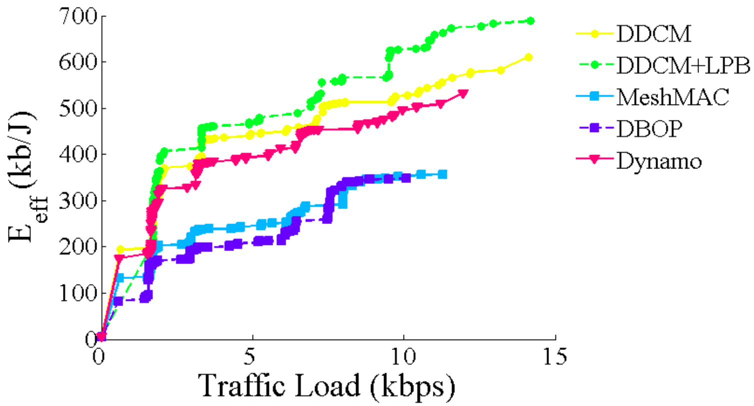
# Evaluation Results




Average Duty Cycle Selected




Probability of Success




Energy Efficiency

# Wireless Sensor Network Design

**Wireless Network Planning Tool**
Optimally placing wireless devices is a challenge, especially for large network deployments.

To **save time and money** during deployment, Nimbus Design Tool can automatically design and optimise the position of wireless devices to meet site specific application needs.

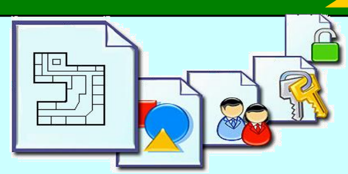
**User friendly GUI >> Minimal Experience Required**

**From Design to Deployment**
With Nimbus Design Tool, designers are aided in all phases of the planning process.
This approach ensures that the user considers the impact of the deployment environment, application requirements, user density, etc on network performance.

**The design tool can also be used to evaluate network expansion or the viability of new wireless applications.**

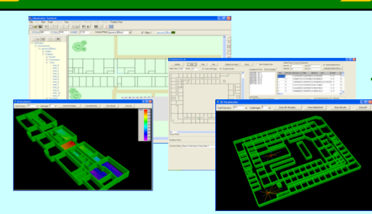
## Wireless Network Design Process

**PHASE 1**



**Requirements Gathering**

**PHASE 2**



**Automatic Design & Optimisation**

**PHASE 3**

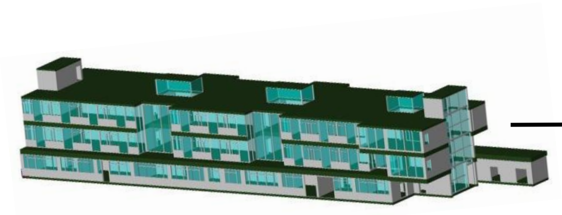
**Deployment**

**PHASE 4**

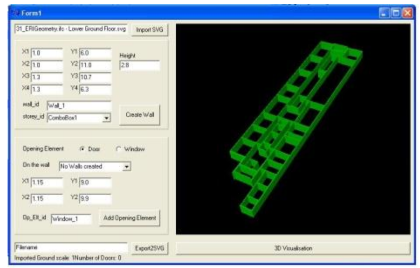
**Verification**


- A. Guinard, M. S. Aslam, D. Pusceddu, S. Rea, A. McGibney, D. Pesch, “Design and Deployment Tool for In-Building Wireless Sensor Networks: a Performance Discussion”, in Proc. 7th IEEE Performance & Management of Wireless and Mobile Networks (P2MNET 2011), Bonn, Germany, Oct. 2011
- A. Mc Gibney, A. Guinard, D. Pesch, “Wi-Design: A Modelling and Optimization Tool for Wireless Embedded Systems in Buildings”, in Proc. 7th IEEE Performance & Management of Wireless and Mobile Networks (P2MNET 2011), Bonn, Germany, October 2011
- A. Guinard, A. McGibney, D. Pesch, “A Wireless Sensor Network Design Tool to Support Building Energy Management”, in Proc. of 1st ACM BuildSys (in conjunction with ACM SenSys), Berkeley, CA, USA, November 2009

# Wireless Sensor Network Design



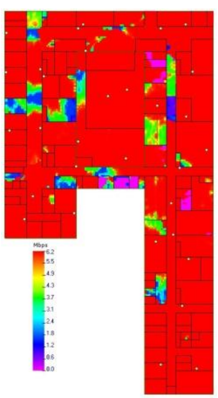
**IFC model or AutoCAD**



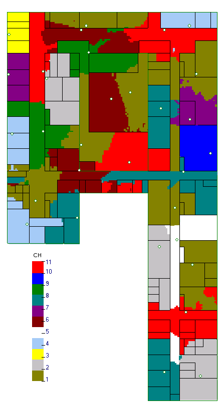
**WSN Design Tool**

**2D Representation for design tool**

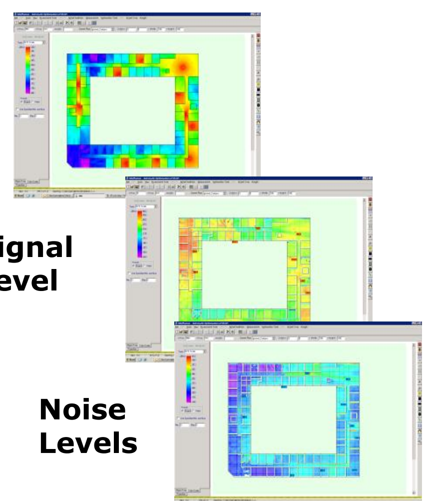
## Design Optimisation Output



**Throughput Prediction**



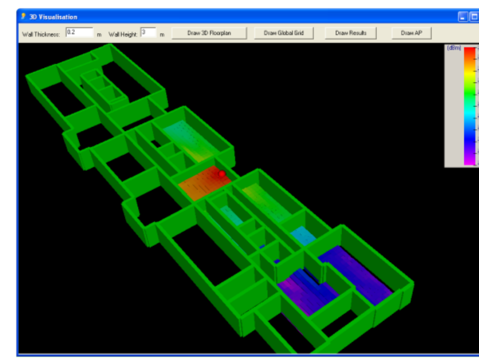
**Channel selection**

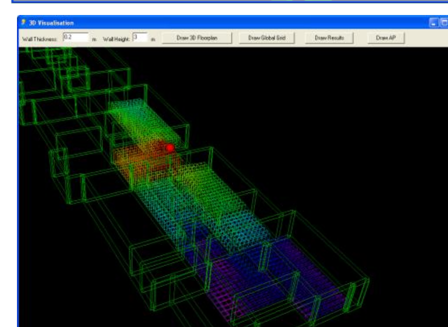


**Signal Level**

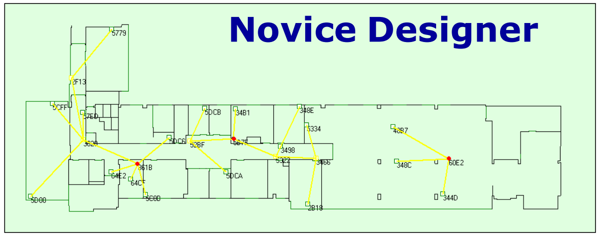
**Noise Levels**

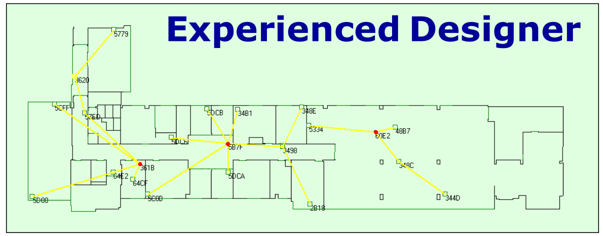
## 3D Output Visualisation

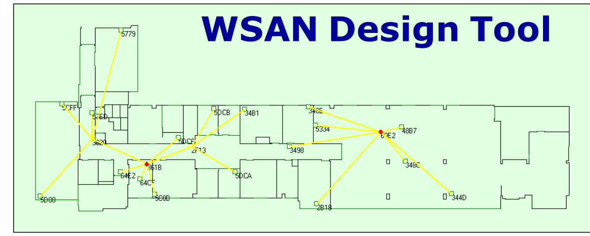


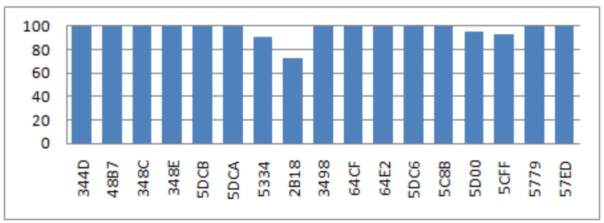


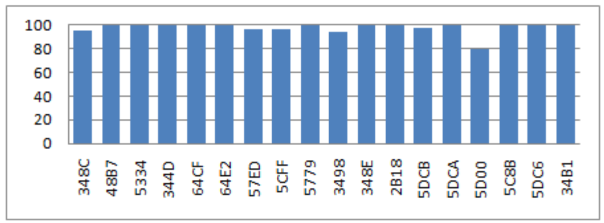
# Design Case Study

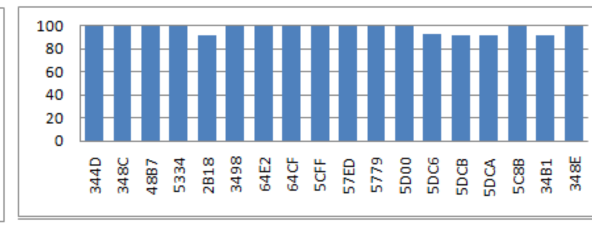


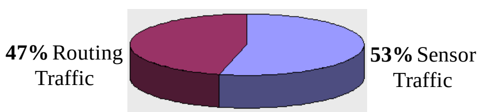



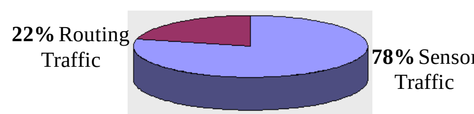



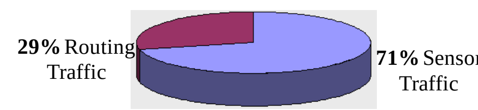




| | | |
|---|---|---|
| 3 Gateways | 5 Repeaters | 3 hops max |

| | | |
|---|---|---|
| 3 Gateways | 1 Repeater | 3 hops max |

| | | |
|---|---|---|
| 2 Gateways | 2 Repeaters | 2 hops max |

| | Sensing Data Delivery Ratio | Data transmission cost (# packets) | Design cost | Cost Savings | Design Time | Comments |
|---|---|---|---|---|---|---|
| Novice Designer | 97.0 % | 1.85 | € 3300 | € 0 | 4 h | No previous WSN design experience, follows EnOcean Range Planning Guide |
| Experienced Designer | 97.6 % | 1.21 | € 2940 | € 360 | 30 min | WSN Design Expert, Sun SPOT developer |
| WSAN Design Tool | 98.2 % | 1.46 | € 2620 | € 680 | 40 min | WSAN Design Tool |

# Road Ahead

- Need to develop concepts for holistic energy management concepts across all protocol layers and sensing/control applications for large scale WSANs
- Design and optimisation methodologies and tools to support better WSAN design considering network and application requirements
- More effective management and diagnostics of WSAN to support long term energy efficient operation

# Acknowledgements

- Financial Support
  - Science Foundation Ireland and Irish Higher Education Authority

sfi
science foundation ireland
fondúireacht eolaíochta éireann

HEA
Higher Education Authority
An tÚdarás um Ard-Oideachas

- Colleagues in Nimbus Centre @ CIT
- ITOBO and NEMBES project Colleagues

itOBO

NEMBES

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