Evolutionary prospective in Wireless Sensor Networks

- Jacopo mondi
- Sistemi e Reti Wireless
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Context

- Low Rate, memory constrained embedded networked devices
- Personal Area networks and small Local Area Network
- Energy efficiency, low cost, limited communication range, self-organization and maintenance,

802.15.4: PHY

- *IEEE Std. 802.15.4-2003*
- 3 different bands, 868, 915, 2450 Mhz band.
- DSSS modulation
- Channel, keying and bandwidth :

Frequency	Channles	Keying	Bandwidth
868Mhz	1	B-PSK	20Kbps
915Mhz	10	B-PSK	40Kbps
2450Mhz	16	OQ-PSK	250Kbps

802.15.4: MAC

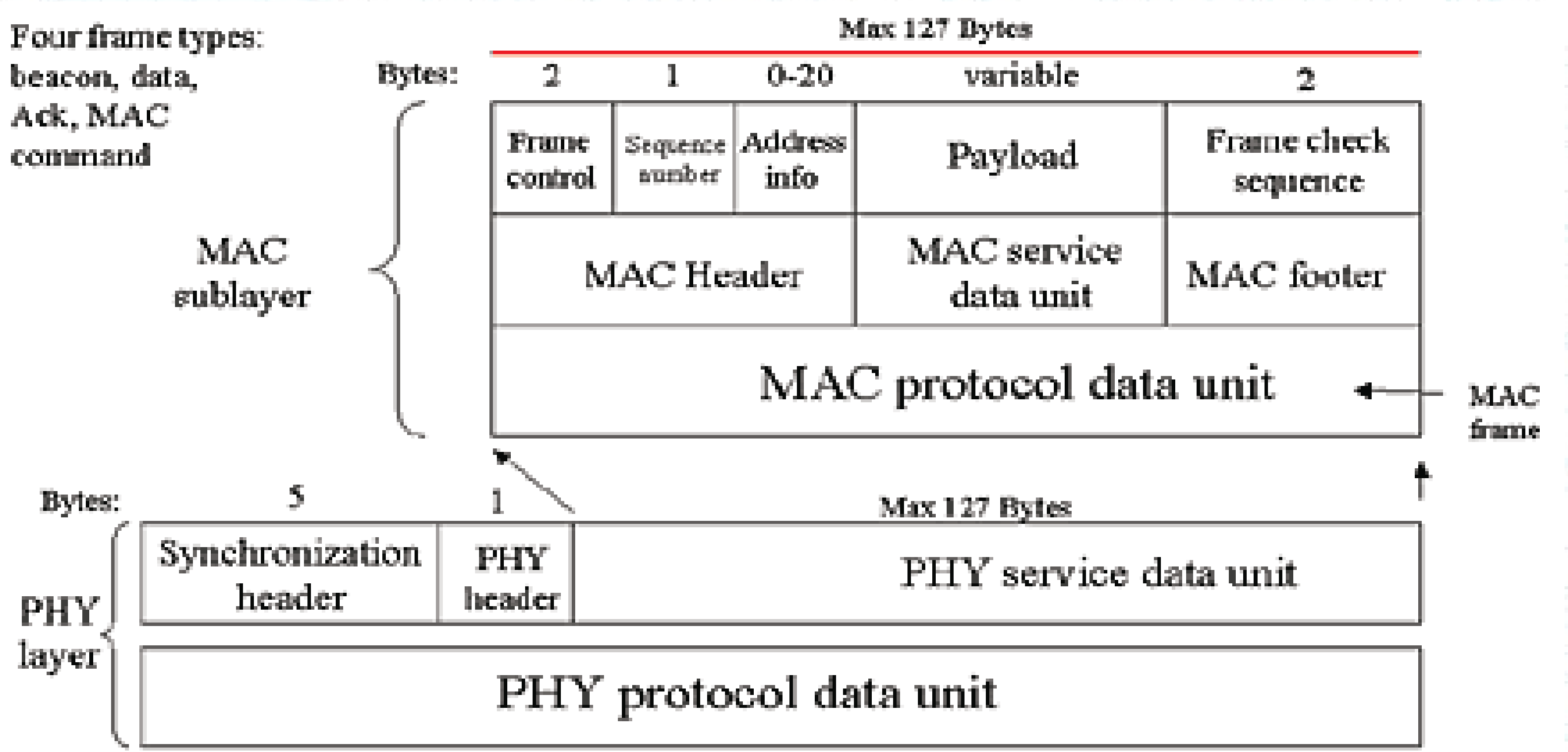
- 802.15.4 admits two different operation modes:
  - *RFD* reduced functions device
  - *FFD* full functions device
  - *RFDs* act as communication end-nodes
  - *FFDs can start and coordinate the network (PAN).*
- Two different supported topology: *star, peer-2-peer.*
- In start network only a FFD can act as (unique) PAN coordinator

802.15.4: MAC

- A PAN coordinator can rule the network in beacon-based or beaconless mode.
- Superframe structure is composed by a *Contention Based Period (CAP)* where channel is accessed using *CSMA/CA*, and a *Contention Free Period (CFP)* where *Guaranteed Time Slots (GTS)* are reserved for other nodes.
- Communication from coordinator to slave is performed in indirect way (announced in beacon or polling)

802.15.4: Frame

- 4 frame structure: *beacon, data, ack* and *control.*
- *MHR* contains addresses and sequencing
- *MSDU* is the MAC payload.



WSN: from *MANET*

- Application context is moving away from the late 90's *MANET (mobile Ad-Hoc networks)* model.
- *IETF MANET Working group (1998):*
  Highly mobile nodes
  High bandwidth
  Power consumption was not considered a real constraint.
- Commercial application and industry evolution are modifying prospective and requirements

WSN: to *ROLL*

- *IETF ROLL (Routing over low power and lossy networks)* (2008)
- New requirements:
  Higher number of (almost) static nodes
  Low bandwidth
  Energy efficiency
  Low memory footprint and code size to fit low cost embedded device
  Geographic distribution and interoperability

So What?

- Flooding based and hierarchical routing protocols developed in the *MANET* prospective do not apply well to new context.

- *WSN* need to exploit the existing infrastructure to communicate and interact with the surrounding environment.

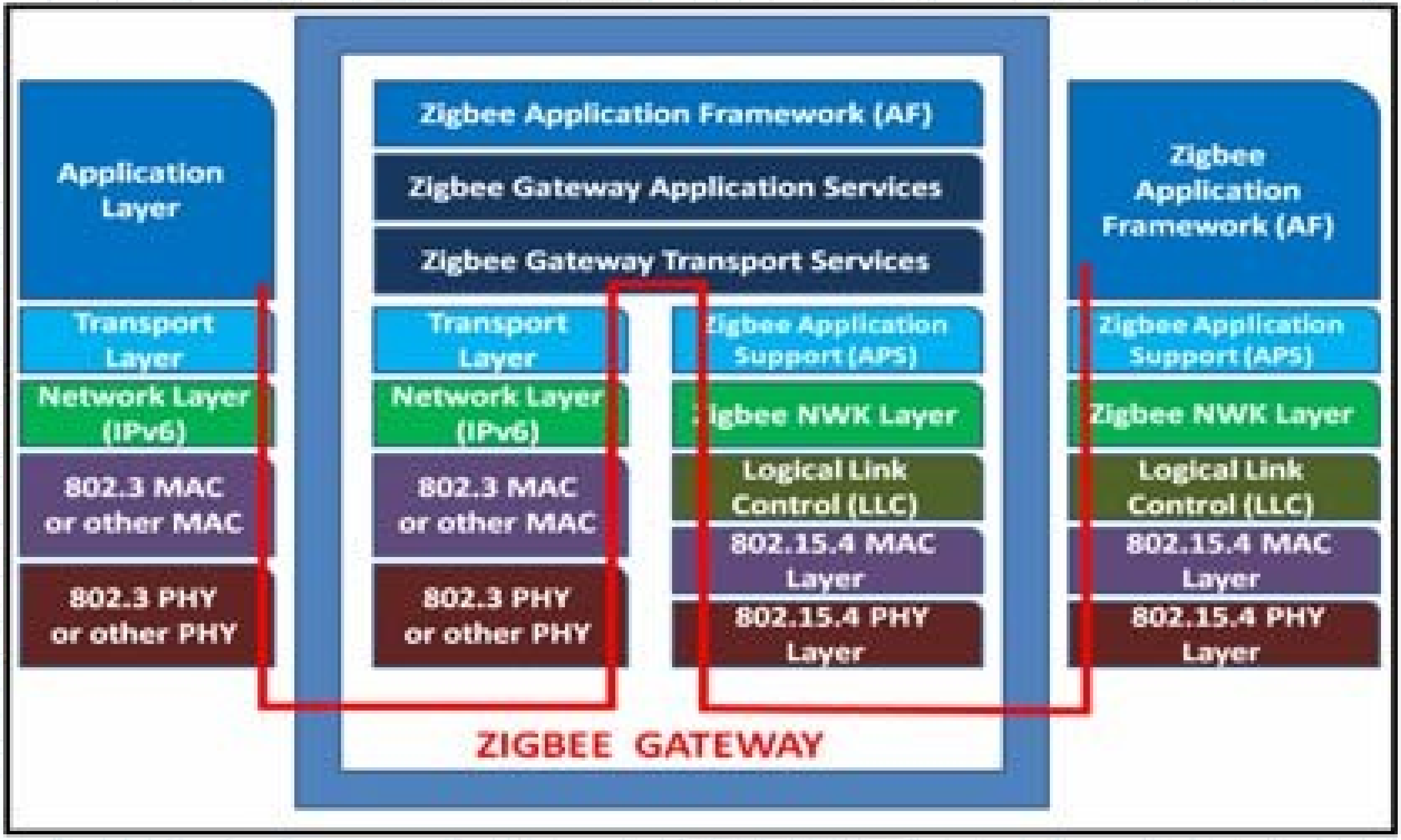
Interoperability

- The ZigBee approach:
  ZigBee-PRO 2009 defines a custom network layer *(NKW)* and a custom set of application facilities to set up a specific network topology and define so-called *ZigBee profiles*
- Routing is heavly topology-dependant.
  For mesh network a reactive *AODV* based routing algorithm is employed. *Start* or *Tree* networks employ address-based hierarchical routing procedures.

Interoperability

- Networking between IP based infrastructure and ZigBee network is complex and require lot of setup.
- IP-Zigbee gateways need to apply conversion techniques in many stack's layers, not only bare header rewriting
- Often an overlay network has to be setup to unify the address space with a virtual address mapping.

IP-ZigBee gateway

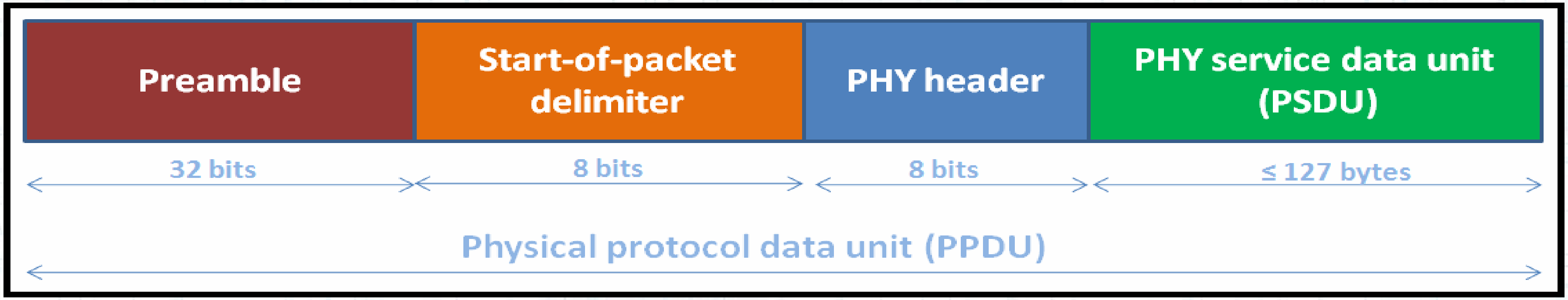


6LowPAN

- To overcome the need of complex and expansive gateways a solution for using Ipv6 as network layer upon lowPANs has been proposed: IETF *RFC 4919, 4944*
- Benefits:
  IP is an open and based on freely available specifications.
  Reuse of infrastructure.
  Reuse of tool and methodologies.
  Direct connection with IP-based devices.

Issues: fragmentation

- IP(v6) specify as MTU 1280 octets. 802.15.4 *PPDU* support at 127 bytes long frames



- A fragmentation-reassembly adaption layer is needed.

Issues: Header size

- IP(v6) header if 40 bytes long. *PPDU* reserve 127 bytes for MAC frames, MAC payload is 102 octets, link-layer security ranges from 21 to 9 octets, IP requires 40 bytes, while TCP and UDP 20 and 8 respectively.
- Very few bytes (~20) are reserved for data payload
- In low bandwidth networks, with low traffic rate, header overhead is more than payload.

Issues: stateless addresses auto-configuration

- MAC 802.15.4 employs a double-addressing schema. *Short (16 bits)* or *Extended EUI-64 (64 bits)* are used.
- A suitable, auto-configurable and stateless methodology to map 128 bits long IP(v6) addresses on 802.15.4 ones is highly desirable.

Issues: TCP/IP for memory constrained devices

- TCP/IP stack has always been considered to heavyweight in terms of both application memory and code footprint to fit a cheap microcontroller.
- Existing implementations are targeted to specific application (control interfaces) or architectures, removing essential TCP mechanism (such as congestion control)
- uIP and the Contiki OS provide a full TCP/IP stack, an event-based API and associated tools (on-the-fly flash, Cooja simulator etc)

6LowPAN: Headers

- 6LowPAN supports 3 different header type
  - Hop-by-Hop options
  - Mesh Addressing
  - Fragmentation
- Hop-by-Hop is the compressed or plain IP header and option
- Mesh addressing admit multi-hop routing
- Fragmentation support packet reassembly on receiver side

6LowPAN: Headers

- Header type is specified in the first two bits. Those bits combined with following 6 produce the *Dispatch byte* that specify how following data has to be handled.
- Different header can be combined in the same frame in the following sequence:

  MESH-FRAGMENTATION-DISPATCH-IP

6LowPAN: Headers

- Admitted dispatch header are:
  01 000001: Uncompressed Ipv6 follow
  01 000010: HC1 compressed IPV6 follow
  01 010000: Broadcast header follow
  01 111111: Additional dispatch follow
- Admitted Mesh addressing header are:
  10 xxxxxxx: Mesh header
- Admitted fragmentation header are:
  11 000xxx: Initial fragmentation identifier
  11 100xxx: Subsequent fragmented

6LowPAN: Dispatch

- To reduce IP header size, HC1 compression schema has been devloped.
- HC1 can reduce header size from 40 to 2 octets.
- Guidelines are:
  - Omit any fields that can be calculated or inferred
  - Compression has to be stateless
  - Support any combination of compressed-uncompressed header.

6LowPAN: HC1 compression

Header Field	IPv6	6LowPAN	Explanation
Version	4	--	Always IPv6
Traffic Class	8	1	Traffic class and flow label are assumed 0
Flow Label	20	--	Otherwise are sent uncompressed
Payload length	16	--	Can be inferred from MAC frame length
Next Header	8	2	Can be only TCP, UDP or ICMP
Hop Limit	8	8	Uncompressed
Source Address	128	2	A bit is used to indicate if address is interface local, and one to indicate if can be derived from MAC.
Destination Address	128	2	A bit is used to indicate if address is interface local, and one to indicate if can be derived from MAC.
HC2	-	1	HC2 compressed header follow
Total	40 bytes	2 bytes	

6LowPAN: Mesh Header

- 802.15.4 do not provide multi-hop forwarding
- A node that need to send a message to a node which is not directly connected to has to specify in the *mesh header* its originator address and the final destination address, and then send the frame to the next hop node

6LowPAN: Mesh Header

- A node that receive a frame with a mesh header has to check final destination address. If the node is the destination it consumes the payload, otherwise has to calculate next hop, rewrite the link-layer source and destination addresses and send the frame.
- Routing algorithm define how the next hop has to be calculated. Mesh header only provide the instrument to specify the final destination and the originator.

6LowPAN: Fragmentation

- Due to the different supported MTU, Ipv6 packets are always fragmented when sent over a lowPAN link.
- Fragmentation header supports the reassembly operation labeling every slice of the same packet with the same identifier and then specifying fragmentation order with an increasing counter.
- A node that receive a fragmented packet has to reassembly until the initially specified total size is not reached.

6LowPAN: Addressing

- All 802.15.4 compliant devices are equipped with and unique 64-bits identifier called *EUI-64*
- When a node join a PAN, a 16-bits identifier is assigned and get used for intra-PAN communication to reduce frame size.
- A 128-bits valid IP(v6) address has to be composed for both the addressing schema.

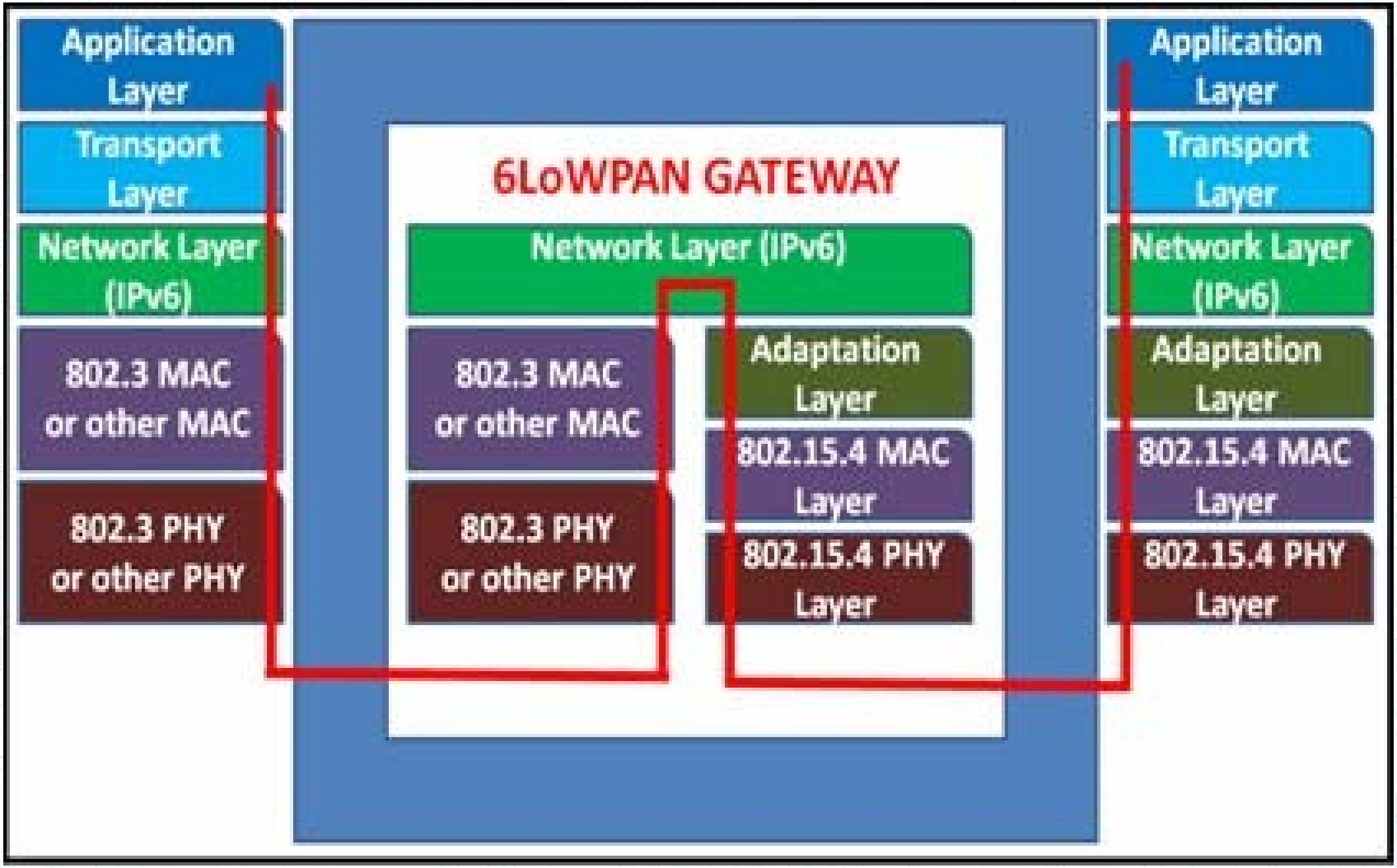
6LowPAN: Addressing

- If a node employ and *EUI-64* address, the 128-bits address is composed as IP(v6) addresses are composed on 802.3 networks (*RA* + *MAC* => *RA* + *EUI-64)*
- If a node employ a short address a pseudo 48-bits address is created: *16_PANID+16_zero+16_SHORT_ADDR*
- The pseudo address is used now as usual on 802.3
- A special bit has to be set to state this is not a globally valid address

6LowPAN: Interconnection

- 6LowPAN is born to reduce the effort required for extending the *WSN* to the traditional infrastructure.
- A light adaption layer is required under the network layer to perform compression and fragmentation-reassembly.
- Addressing between IP(v6) network and 6LowPAN *WSN*, is totally transparent, as all the adaption mechanism happens between the MAC layer and the IP one.

6LowPAN: Interconnection



WSN: Routing prospective

- Paradigm shift from *MANET* to *ROLL*, dictate for a novel approach to the routing problem in *WSN.*
- Protocol created for *MANET* are essentially based on flooding or clustering.
- *ROLL* working group is defining new algorithms based on geographical approach based on self-organizing coordinate systems.

Routing: Flooding based

- Evolved from naive data flooding approach to control messages approach.
- *AODV* and *DSR* are most famous examples.
- Optimization for *WSN* have been defined in the years: *DYMOlow, LOAD*

Routing: DYMO(low)

- AODV based
- Path accumulation during route creation to distribute path knowledge between nodes.
- Admit weight assignments to edges.
- DYMOlow optimized for WSN: do not use UDP as DYMO but operates on the link layer directly.
- Use 16 bit addresses.
- Do not support local repair and cost accumulation

Routing: LOAD

- LoWPAN Ad-Hoc On-Demand Distance vector. AODV based.
- Do not use sequence number. Prevent early RREP to avoid loop formation
- Do not use precursor list to simply routing tables. Upstream node tries to repair a broken link. If unable unicasts a RERR to the originator.
- Not use *hello messages* but instead link layer ackoledgments.

Routing: Flooding issues

- Designed for a small number of mobile network devices.
- No power saving policy in routing procedures.
- Flooding (even control messages) is a big overhead if network mobility is reduced.

Routing: Cluster based

- Based on hierarchical network organization.
- Data goes from cluster member to coordinator. Coordinator forwards to the sink node.
- Impose distributed coordination to elect cluster head.
- Limit the flooding area to the cluster members.

Routing: Cluster based

- *LEACH:* distributed election of cluster head. Use TDMA for inter-cluster communication and CDMA for intra-cluster.
- *HEED:* head selection based on residual energy. Based on the radio power tuning to limit communication range.
- *APTEEN:* limit the sensed data to a maximum number of generated packets.
  Provides a multi-tier organization (complex formation and join)

Routing: Cluster based issues

- Number of clusters grows with the number of nodes.
- Coordination for cluster-head election and cluster maintenance is expansive.
- Since nodes use lossy-links is complex to guarantee data consitency.
- No cluster based algorithm standardized or in use in commercial applications.

Routing: geographic routing

- Routing choices based on location awareness.
- Different approaches: *greedy, face routing*
- Require operations on the graph structure, such as planarization and edge transformation.

Routing: geographical greedy

- Given a source and a destination, a specific metric, such as:
  - distance from the line connecting the nodes
  - absolute distance
  - node projection position

  determinate the next hop node.
- Vulnerable to *void areas,* when a node has no neighbors closer (respect a given metric) to the destination then itself.

Routing: Face routing

- When a void area is met a method to circumnavigate the area is required.
- Mixed techniques such as *Greedy-Face-Greedy (GFG)* (act as face only when needed).
- Face routing employ right hand rule: packets roll to 'the right' on edges.
- When void area is passed algorithm returns greedy.
- Planarization is mandatory to avoid loops (Gabriel Graph transformation)

Routing: geographical issues

- Location-awareness is expansive: it costs money if GPS is needed, it cost maintenance if setup has to be done by hand.
- Planarization requires that nodes knows exactly their positions. Wrong decisions can cut off communications links.
- Absolute coordinates can be replaced by virtual coordinates defined upon the network topology and the node relative positions.

Routing: Self Organizing

- Having each node knowing the exact location comes at a price
- Replace absolute GPS coordinate with virtual coordinate systems.
- Apply geographical routing inspired protocols onto virtual coordinates.

Routing: Inferring location

- Anchor nodes know their exact locations.
- Other nodes use local measurement and localization to infer their position
- *Multilateration:* knowing distance from a set of anchor nodes is possible to determinate relative positions.
- Position is intersection of circles centered in the anchor locations with relative distances as radius.
- Distance approximation can be defined in terms of *hops*, *RSS* and *TOA*

Routing: Inferring location

- *GPS Free Free:* localization with 40mt approximation, with 10 neighbors per node.
- Greedy routing algorithms performs worse than when using real coordinates.
- **Why?** Geographical proximity does not mean electromagnetic proximity.
- Close node cannot always communicate. Node that can communicate are not always close.
- Real life experience VS simulation

Routing: Virtual coordinates

- Coordinate system must reflect the network topology.
- Virtual coordinates: vector *{V1,...,Vn}* *Vi*:distance from anchor *i, N: anchors*
- Anchors broadcast a counter, incremented at each hop.
- Virtual coordinates are not related to geographical coordinates

Routing: Virtual coordinates

- A notion of distance based on virtual coordinates is needed
- Euclidian distances on vectors
- Simulation results: less void spaces encountered, greedy algorithms performs better then when used with real coordinates.
- **Very promising approach**

Routing: Virtual coordinates

- **BVR:** anchor nodes randomly chosen.
- **Vcap:** greedy forwarding, anchor nodes elected at edges of network
- **Vcost:** cost-over-progress instead of greedy
- **S4:** anchor nodes beacon that are transmitted via flooding. Each node track closest beacons and next-hop to reach beacon's source. Network gets 'cluster-ized': each cluster for node *s* is formed by nodes that are closer to *s* then closest beacon.

Routing: Virtual coorindates

- PROS:
  - Geographical routing algorithms performs better when applied on virtual coordinates systems.
  - Virtual coordinates reflect network topology and not geographical distribution.
  - Virtual coordinates are cheaper
- CONS:
  - Electing anchors is complex
  - Node need to share information on global state: consistency check.
  - Sub-optimal solutions generally found.

Routing: Gradient routing

- Virtual coordinates systems admit **real** peer-to-peer traffic.
- P2P traffic is not a stringent requirement for *ROLL* (it was for MANET)
- In modern WSN data are supposed to flow from single sensors to sink nodes.
- Traffic model is more similar to MP2P.
- Gradient routing is a simplification of virtual coordinates systems.
- Simpler to implement and to deploy in real systems.

Routing: Gradient routing

- Basic idea:
- **Each node acquire and 'height', that represent the distance from the sink, calculated as a function of some chosen metric (latency, energy consumption, SNR, delivery rate)**
- A set of heights represents a **gradient**.
- Different gradients exist in same network. Each gradient is targeted to a specific function.

Routing: Gradient routing

- Convergecast networks:
  - Simplest convergecats: 1 sink, n-1 nodes
- Node marked with a gradient
  - Simplest gradient: hop count from beacon
- **GBR:** gradient based on energy threshold
- **GRAB:** gradient built by sink propagating advertisement packets. Cost is minimum energy overhead (incremental) used to forward that packet. Energy overhead estimated using SNR. 90% delivery ratio with minimal energy.

Routing: Gradient routing

- **RPL (Routing protocol for low power and lossy networks)**
- Gradient:
  - Set of sink nodes
  - Set of atomic meters collected (bandwidth, delivery ratio etc)
  - How atomic meters are combined to obtain a cost.
  - How link costs are combined to obtain a multi-hop path cost.
- A single network can contain more gradients.

Routing: Gradient routing

- Different gradients: depending on WSN constraints:
  - Energy monitoring: cost is power consumption. Latency is not a constraint but network lifetime is.
  - Smoke alarm: cost is network latency between nodes and delivery ratio. Energy is a minor constraint because transmission is sporadic.
- Different functions on same WSN=different path selection.

Routing: Gradient Routing

- RPL is strictly compliant with IP(v6)
- Signaling used to setup gradients are sent as options in *IP(v6) Router Advertisements* packets.
- *RA* are periodically exchanged between nodes.
- *RA* period can be dynamically calculated to archive a better energy efficency.

Future developments

- RPL is still in standardization phase (early 2011).
- Future dominant topics:
  - Mobility (back to MANET??)
  - Scalability
  - Node heterogeneity
  - Security concerns.
- Few devices will be powered with batteries: energy harvesting
  - Routing must adapt to energy harvesting, to find out which path has as enough energy