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A technical survey on medium access control and routing protocols in wireless sensor networks for the active aircraft

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A TECHNICAL SURVEY ON MEDIUM ACCESS CONTROL AND ROUTING PROTOCOLS IN WIRELESS SENSOR NETWORKS FOR THE ACTIVE AIRCRAFT

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Executive Summary

This report presents a review of the state-of-the-art medium access control and routing protocols for wireless sensor/actuator networks (WSAN). A topological WSAN design is introduced as part of the solution for decentralised local and centralised global control problem for the Airbus/ESPRC Active Aircraft Project. Following this, candidate protocols for implementation in real environments and applications are identified, classified and evaluated according to the technical requirements of active airflow control.

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Medium Access Control and Routing Protocols in Wireless Sensor Networks for the Active Aircraft

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1   Introduction

As expressed jointly by EPSRC and Airbus, it is a very important challenge to create an efficient "nervous system" in aircrafts for the interconnectivity and control of all on-board active systems, such as airflow control, load control, structure and system health status monitoring. Such a nervous system can significantly improve flight safety, reduce skin friction drag and increase fuel efficiency. If it is successful, it can be installed in aircrafts in a commercial manner. Our contribution to the Active Aircraft vision is to integrate wireless sensor/actuator network (WSAN) technologies to the nervous system. The integrated system will demonstrate active airflow control over aircraft wings and airfoil. It will also demonstrate health status monitoring of these components as well as the engines. The system consists of the following modules:

- Application-specific wireless and fibre-optic sensors to collect measured aerodynamics and health status data on the wings, airfoil and engines;
- A central active control system to interpret the information aggregated through wireless sensor networks and to feed back actuator control commands;
- Wireless actuators to realize the active airflow control.

All modules will be interconnected by a transparent, reliable and efficient communication infrastructure, which comprises the backbone and end points (i.e. sensors and actuators) of the active aircraft nervous system. Figure 1 shows the functions and interactions between the various components of the proposed integrated nervous system.

In the current first year of the Active Aircraft research programme, our major task is to investigate the technical requirements of active airflow control and develop suitable communication protocols for wireless sensor networks (WSN) to support the integrated nervous system vision described above.

The Active Aircraft scenario requires distributed local and centralised global control. In addition to the centralised closed-loop control approach, distributed open-loop control algorithms require the sensors to process the sensed data locally, make quick control decisions, and then directly communicate with their neighbouring actuators to take control actions. Both active control approaches raise stringent performance requirements on communication algorithms, especially in terms of delay, loss and throughput, which are related particularly to medium access control (MAC) and routing algorithms. The ultimate goal is to disseminate data from sensor nodes to the sink in an energy and quality of service (QoS) aware manner, so that the lifetime of the sensor network is maximised.
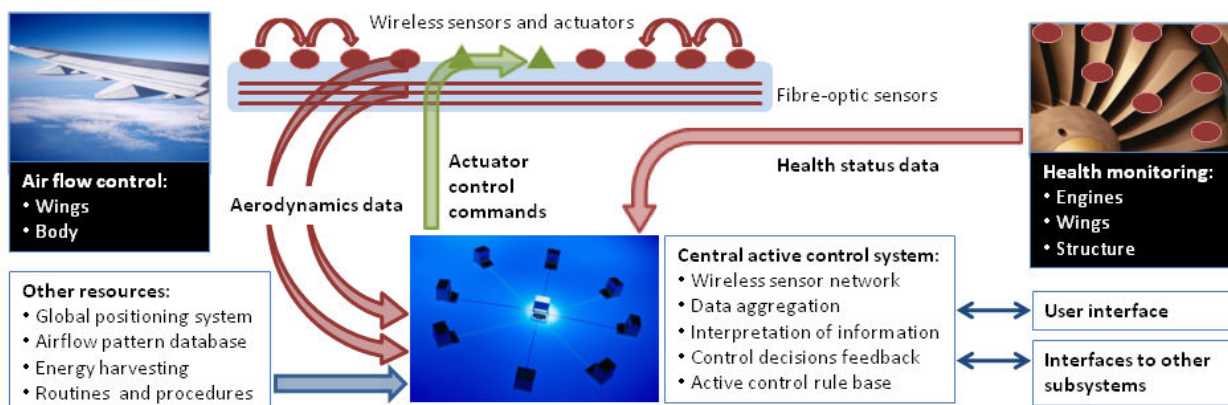
Figure 1: An integrated aircraft nervous system for active flow control and health monitoring.

The rest of this report is organised as follows. Section 2 introduces the topological design of the WSAN that we intend to use for both the centralised as well as the decentralised active control applications for Active Aircraft. In Section 3 and Section 4, state-of-the-art MAC and routing algorithms for WSN are evaluated, respectively. In both sections, key design considerations and assumptions for the Active Aircraft scenario are identified and the protocols with potential applicability are reviewed. A summary of the evaluation is given at the end of each section. Finally, Section 5 concludes the report with final remarks and some future work.

2   Topological Design of a Sensor/Actuator Network for Active Aircraft

The WSAN for the active aircraft flow control application is expected to comprise of a high density of sensor nodes (SN) and a lower density of actuator nodes (AN) uniformly distributed over the relevant surfaces of the aircraft. Thus, a grid or mesh like wireless network topology is expected. To enable fast, decentralised active control, the SNs are organised into local 'patches' comprising of a central AN surrounded by several SNs responsible for providing to the former relevant raw or pre-processed measurement data for making real-time control decisions. This is illustrated in Figure 2.

Furthermore, ANs process the data received from the SNs and send this processed data to a central aircraft control system to enable the latter to adapt AN parameters to the measured airflow and thus implement (slow) centralised active control. Unlike the communication between the SNs and the AN in a patch, which takes place locally in the vicinity of the surface being monitored, the communication between the ANs and the central controller is not local. Thus, the central controller is reached via a central 'aircraft bus' through which all aircraft control systems connect with the central controller. Therefore, wireless gateways to the aircraft bus are strategically located to provide connectivity between the WSAN and the aircraft bus. This is illustrated in Figure 3.

Figure 2: Decentralised, fast active flow control using convergecast

Figure 3: Centralised, slow active flow control using convergecast/unicast.

As shown in Figure 2, the local patch communication displays a convergecast pattern, as SNs send measurement data to the local AN. Thus, SNs in a patch are arranged into 'tiers', with the lowest tier comprising of nodes at the boundary of the patch. SNs in each tier are grouped into 'clusters' with the cluster head being a node in the next higher tier, with the cluster head of the highest tier being the AN. Since the AN in the centre of a patch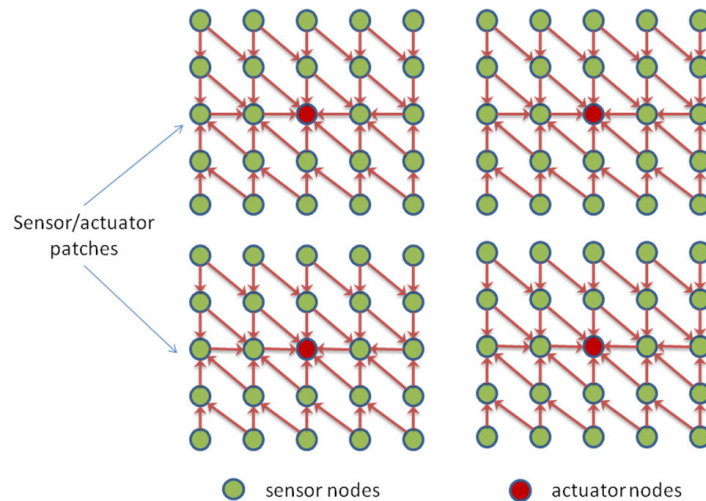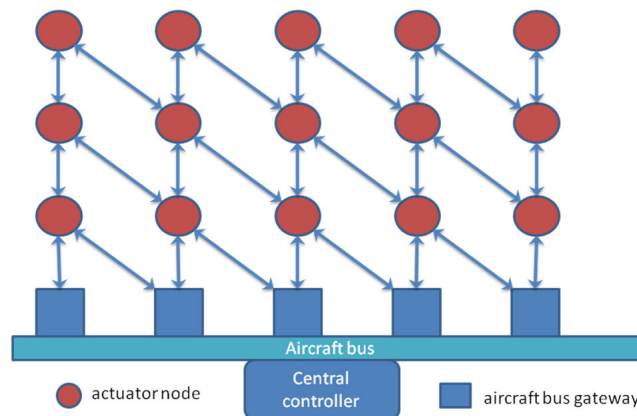 is surrounded by SNs with high density, the flow of sufficient information is guaranteed regardless of the direction or speed of the aircraft. In other words, the direction of communication can be configured and reconfigured under both subsonic as well as supersonic flight conditions. Furthermore, SN measurements in a patch are highly correlated and thus the data generated by the SNs in a patch will display a lot redundancy. For example, when a SN cluster head receives measurements from its 'children' SNs these measurements are correlated with each other and with that of the cluster head. The cluster head can, thus, combine these measurements into a single more accurate measurement. In the highest tier, the AN receives correlated measurements from its children SNs and combines these measurements to give a single control decision metric. Thus, this local patch data redundancy is exploited using the convergecast communication pattern to filter out erroneous readings and to improve the overall accuracy of the measurements.

Communication between the ANs and the aircraft central controller, unlike the local patch communication, is bi-directional. When ANs send data to the central controller (uplink), a convergecast pattern is used. However, unlike the SN data communication in a local patch, the AN data is sent on an individual basis to obtain individual (unicast) control feedback from the central controller on the multi-hop downlink. Therefore, ANs are arranged into 'tiers', with the lowest tier comprising of nodes at the boundary of the patch, with the cluster heads of the highest tier being the APs to the aircraft bus.

Given the high density of sensor and actuator nodes to be deployed for active flow control, the aggregate power consumption requirements could be very high. This is expected to significantly impact fuel economy, if some or all of this power is supplied by the aircraft. At one extreme, if only (re-chargeable) battery powered nodes are used, which maximises the fuel economy, the energy resource becomes limited, and conserving energy is even more crucial. Even if ambient energy harvesting is employed to re-charge node batteries, the energy resource is still limited by the fact that the power consumption cannot exceed the rate at which energy reserves are replenished. However, it is expected that some nodes will rely on the aircraft power supply, such as ANs which have high power requirements for actuation, processing and communication. Some SNs may also be powered by the aircraft to provide added design redundancy and thus enhance overall network reliability. Therefore, maximizing the energy efficiency of the WSN is an important design goal regardless of how the network is powered.

3   Medium Access Control

In this section, we first define the application-level requirements for MAC protocols implementation in the Active Aircraft Project, with an emphasis on the requirements for the decentralised and centralised active control schemes outlined above. Based on these criteria, a short list of potential candidates is selected from across the design space of existing wireless sensor MAC schemes. These MAC protocols are evaluated and compared against each other, with the aim of identifying the most appropriate MAC design space for the active aircraft application.

3.1   Design Considerations for Active Aircraft MAC

This section lists requirements for MAC protocols to enable both fast, decentralised and slow, centralised active flow control. These requirements fall loosely into three groups, namely system constraints imposed by data patterns and network topology, performance requirements and essential design features.

3.1.1   Clustered Network Topology

A multi-tier, clustered network topology is required to support the convergecast communication pattern of the WSN at both the local (patch) and network-wide level. The MAC protocol must be capable of efficiently operating over this network topology, as well as effectively exploiting the unique features of this topology to maximise performance. At the network-level, the MAC must support downlink unicast communication, as well as uplink convergecast communication, and thus support for bi-directional communication is required at the network level.

3.1.2   Periodic Data Flow

The periodic sensor measurements will tend to generate a periodic data flow of processed and pre-processed sensor data from the SNs to the AN of any given patch. This implies a schedule-based MAC approach, in order to effectively exploit this pattern to maximise performance. Some spatial correlation between sensor measurements of the airflow boundary layer at the patch level is expected. The MAC protocol must have the ability to manage the local (patch) data communication in a manner that enables this available data redundancy to be exploited.

3.1.3 High System Spectral Efficiency

The periodically generated sensor data requires real-time processing and delivery to the AN to implement real-time, decentralised flow control. Maximising the system spectral efficiency (throughput per unit bandwidth per unit area) in the multi-hop sensor network is essential to minimising latency and maximising energy efficiency. Thus, it provides the single most important performance metric of the communication system of the active flow control application. Therefore, a high system spectral efficiency MAC protocol is required that minimises data forwarding delay between tiers and maximise the number of clusters communicating simultaneously on the same tier and frequency.

3.1.4 Interference Awareness (Receiver Channel Sensing)

While intra-cluster interference is completely avoided by the clustered network topology, interference management between clusters is a major challenge for the MAC protocol. Interference can be managed by centralised scheduling coordinated by the parent node of the highest tier. However, without receiver channel sensing, this results in either over-provisioning at best or poor interference management at worst, both of which deliver poor system spectral efficiency. Receiver channel sensing requires that scheduled transmitters listen for feedback signals from receivers in other clusters in their vicinity to determine (based on channel reciprocity assumptions) whether they can transmit without causing unacceptable interference to these vulnerable receivers. This information can be used by the parent nodes to optimise the schedule to maximise system spectral efficiency.

3.1.5 Minimum Handshaking Overhead, Idle Listening and Overhearing

Sender-receiver handshaking via request-to-send (RTS) and clear-to-send (CTS) messaging prior to data transfer (DATA) is unnecessary for deterministic periodic data, and yields potentially significant overhead given that sensor data typically comprises of short bursts of data. However, receiver acknowledgements (ACK) provide a powerful means of enabling interference awareness. Therefore, MAC approaches with DATA/ACK are preferable to RTS/CTS/DATA access. Furthermore, idle-listening to channel activity and overhearing data of other links must be minimised to enhance energy efficiency since, while enhancing the interference management capabilities, they consume a lot of energy.

3.1.6 Minimum Storage of Neighbourhood States

Neighbourhood data is required to know what nodes are communicating, their bandwidth requirements and channel allocations, as well as what nodes are available to relay data to the next hop neighbour and the quality of communication on each one. However, given the high density node deployment and the need to maximise the use of the limited storage resources available for distributed processing of the sensor data, it is essential to minimise the amount of neighbourhood data stored at each node.

3.1.7 Scalability, Self Healing and Adaptability

The MAC protocol must be capable of supporting a high density WSN with multi-hop communication. It must able to quickly recover and reconfigure the network connectivity and update the transmission schedule in the event of unpredictable changes such as, sudden node unavailability or recovery of a previously unavailable node, which impact on the traffic and interference patterns.

3.2 Review of WSN MAC Protocols with Potential Applicability

The following is a sample of the leading WSN MAC protocols, spanning the entire design space of the current state-of-the art. These protocols are briefly presented here, with more details available in [1]-[4]. A more comprehensive list of WSN MAC protocols are provided in [5]-[11].

3.2.1 Sensor-MAC (S-MAC) and Timeout-MAC (T-MAC)

In S-MAC [1], all nodes periodically listen, sleep and wakeup, with all nodes synchronizing the start of their active and sleep periods. Nodes listen and send data (using RTS/CTS handshaking) during the active period and turn off their radios during the sleep period. The goal is to control the duty cycle to tradeoff higher delay for lower energy consumption. T-MAC [1] modifies S-MAC by using a very short listening window at the beginning of each active period, which results in an adaptive duty cycle. The start of active periods remains synchronized and thus T-MAC inherits the inter-tier data transfer delay problem of S-MAC.

The main drawback of S-MAC and T-MAC is the synchronised start of active periods among all nodes which results in high latency for convergecast communications because nodes are delayed from transferring data from one tier to the next by sleep intervals. Furthermore, this results in energy wasteful overhearing/idle listening. In addition, the RTS/CTS handshaking results in significant spectral inefficiency.

3.2.2 Data-gathering MAC (DMAC)

DMAC [1] addresses the latency issue for the convergecast communication pattern. The basic idea is to stagger the active times according to the tier level such that data can be quickly transferred from one tier to the next without little or no sleep interruptions. Tiers enter sleep mode when not sending to higher tiers or receiving data from lower tiers. DMAC uses simple CSMA with acknowledgements.

DMAC improves on the latency performance of S-MAC and T-MAC for convergecast communications, and avoids the RTS/CTS overhead. However, it is not interference aware, which implies that interference can only be avoided by over-provisioning resulting in poor system spectral efficiency. For example, DMAC provides no mechanism of mitigating interference between clusters on the same tier, and precludes the possibility of higher tiers simultaneously reusing the same channel as lower tiers. Furthermore, DMAC does not support bi-directional communication as required for communication between ANs and the central controller.

3.2.3 Low Power Listening (LPL) and Synchronised Channel Polling (SCP)

LPL [2] dispenses completely with the synchronized active/sleep approach but rather uses receiver channel polling to reduce the energy spent on listening for incoming messages. Furthermore, it uses a simple DATA/ACK scheme, which minimizes overhead. Instead of simply turning the radio on, LPL periodically checks the channel, where the length of the preamble of each message includes two poll periods to ensure that a message is not missed. Therefore, receiver energy efficiency is gained at the expense of the sender. Furthermore, LPL is not scalable and is very sensitive to node density and traffic rate.
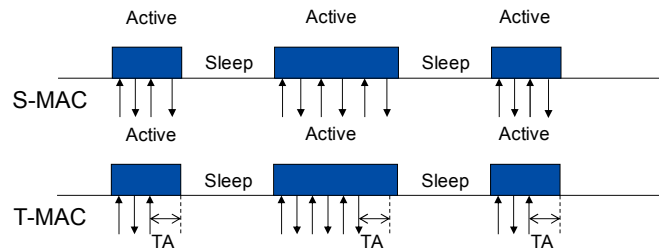

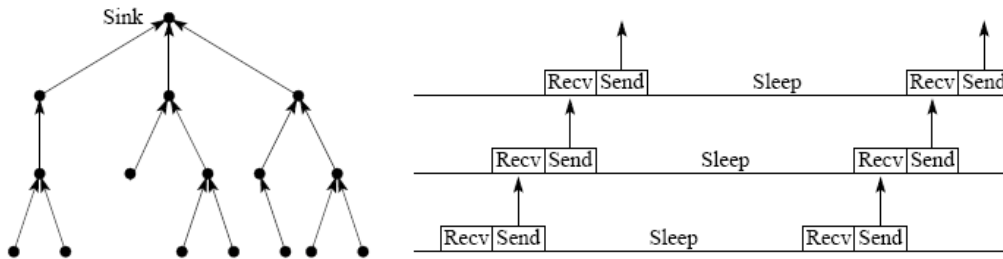**Figure 4: Illustration of S-MAC and T-MAC**

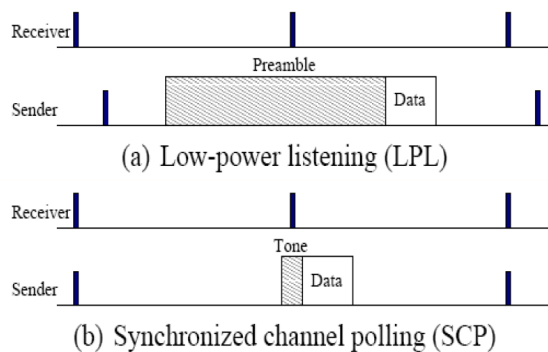**Figure 5: Convergecast tree with matching, staggered DMAC slots.**

Figure 6: Illustration of LPL and SCP

The channel polling mechanism of LPL has been refined in the SCP [3], which uses channel polling, but synchronizes all nodes to poll at the same time. Thus, the message preambles are not stretched for a complete poll period because the poll moment is known. In addition, the SCP approach allows potential senders to do contention resolution before the intended receiver wakes up. A node that wants to send a message chooses a random moment within the contention window at the start of each slot. If the channel is clear at that moment, the potential sender switches on its radio, checks the channel and starts sending a preamble. The preamble acts as a busy tone and continues until the end of the contention window locking out any other potential senders. Right after the end of a contention window all nodes except the winner, if any, wake up and perform a carrier sense to see if there is a preamble followed by a message.

SCP improves on LPL in terms of energy efficiency. Furthermore, in the absence of sleep period interruptions between hops and as contention for the channel takes place at the start of each slot, it potentially supports lower-latency multi-hop communication than T-MAC or S-MAC. However, the sender contention mechanism and receiver channel polling are unnecessary features in a clustered network with periodic data, where the parent nodes control intra-cluster channel access, and thus constitute waste in terms of channel utilisation and energy. Furthermore, the use of a transmitter busy tone does little to mitigate inter-cluster interference because of the hidden node problem.

3.2.4 Lightweight MAC (LMAC)

The LMAC protocol [4] uses a distributed slot selection mechanism based on two-hop neighbourhood information. Each node owns a fixed-length time slot, in which it always transmits a header, optionally followed by a payload. The header contains various fields including the destination and length of the data payload. To facilitate new nodes joining the network, each header includes a bitmap detailing which slots are occupied by the one-hop neighbours of the sending node (i.e., the slot owner). By ORing the occupancy bitmaps of all headers in a frame, a new node can easily determine which slots are still available in its two-hop neighbourhood. It randomly selects one of those as its own and starts sending out headers to actually claim it. In the unlikely event of two nodes joining at the same time and selecting the same free slot, a collision occurs resulting in garbled headers. A neighbouring node observing this (i.e., the header checksum fails) will broadcast the involved slot number as part of its header, signalling to new comers to back off and try again.

The major drawback of this approach is that it is not scalable, as the number of nodes in any two-hop neighbourhood cannot exceed the number of slots in a frame, which needs to be fixed before deployment. Choosing a large number of slots per frame leads to over-provisioning (wasted slots) and protocol overhead (large bitmaps), whereas choosing a low number may lock out nodes in (dense) deployments. Furthermore, the LMAC bitmap broadcasts are an unnecessary overhead in a clustered network, and the fact that slot allocation process lacks interference awareness results in low system spectral efficiency.

3.2.5 Crankshaft

The basic principle of this protocol [4] is that nodes are only awake to receive messages at fixed offsets from the start of a frame. Allowing different nodes to wake up for reception at different offsets from the start of the frame means reduces overhearing messages and idle-listening. The Crankshaft protocol divides time into frames, and each frame is divided into slots. The slot a node listens to is determined by the node's MAC address. Therefore, a node wanting to send a message knows precisely in which slot the destination wakes up. Crankshaft uses a DATA/ACK sequence for unicast messages, and the slot length is such that it is long enough to accommodate both.

Special provisions are made for base-station or sink nodes. Sink nodes will listen to all unicast slots. The rationale for this is that the sink is the destination for most traffic in the network and therefore requires more receive bandwidth. Furthermore, the sink typically is less constrained in terms of energy resource, which will allow it to spend more energy.

The main disadvantage of the crankshaft protocol is that it is not scalable, with channels allocated statically, without interference awareness and independent of the traffic load. While this is suitable for intra-cluster communication or low density multi-hop communication, it leads to poor performance in high density applications.

3.3 Numerical Comparison

In this section, the performances of five of the above protocols are compared quantitatively: LPL, T-MAC, LMAC, SCP-MAC, and Crankshaft. The experimental setup [4] includes 96 nodes on a field of approximately 90×50 m. The simulated nodes have a radio range of 25 m, which is similar to the radio range in the real-world experiment. The base station is situated near a corner. A convergecast communication pattern is considered. Routing is done using a static routing table. Figure 7, Figure 8 and Figure 9 show the delivery-ratio, energy-consumption and latency performance, respectively, of the investigated protocols.

The LPL protocol has the highest delivery ratio except for high message rates, but at the expense of consuming a lot of energy. The high energy consumption is due to the fact that nodes with data to send freely contend for the channel with long preambles every hop. As nodes using LPL can send their message any time, i.e., they do not have to wait for a slot or frame to start, the latency remains low until the network is saturated. The SCP-MAC protocol improves significantly on the energy efficiency of LPL (by a factor of 2) with its shorter preambles, with only a moderate decline in delivery ratio low message rates. At higher message rates SCP-MAC provides the highest delivery ratio, and delivers the best overall latency performance.
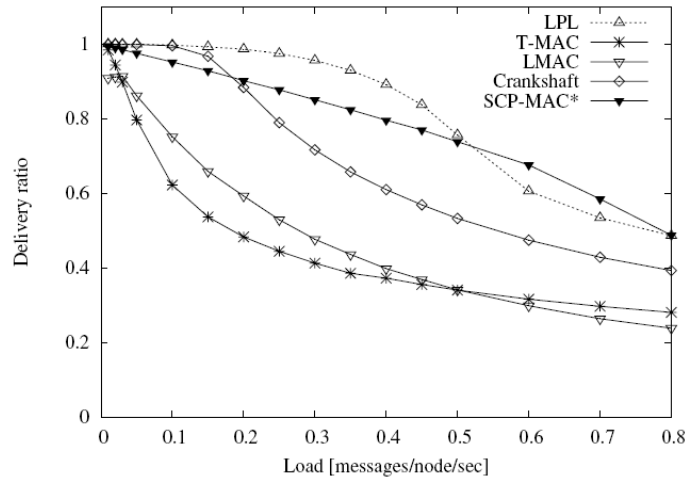

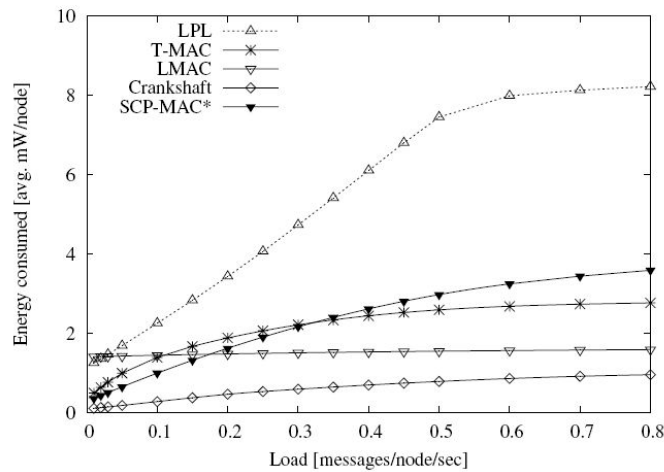**Figure 7: Delivery ratio performance.**
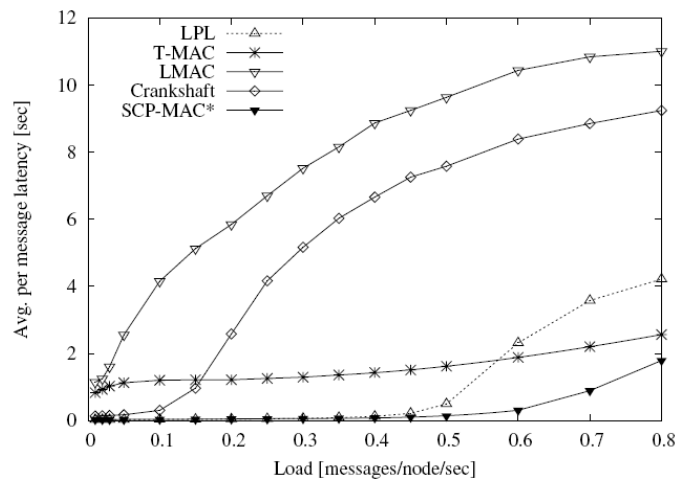

Figure 8: Energy consumption performance.

Figure 9: Latency performance.

Table 1: Characteristics of WSN MAC protocols

Protocol	Low latency multihop	Bidirec-tional	Periodic data	Spatially correlated data	System spectral efficiency	Inter-ference aware	Overhead	Idle listening + over-hearing	Scalable + traffic adapt-able
S-MAC	No	Yes	No	No	Low	Yes (with RTS/CTS)	High (RTS/CTS)	Low	No
T-MAC	No	Yes	No	No	Low	Yes (with RTS/CTS)	High (RTS/CTS)	Low	No
DMAC	Yes	No	No	Yes	Low	No	Low (ACK)	None	Yes
LPL	No	Yes	No	No	Low	No (hidden node problem)	High (long preamble)	Low	No
SCP-MAC	No	Yes	No	No	Low	No (hidden node problem)	Low (short preamble)	Low	Yes
LMAC	No	Yes	Yes	Yes	Low	No (hidden node problem)	High (bitmap slot scheduling)	None	No
Crankshaft	No	Yes	Yes	Yes	Low	No (hidden node problem)	Low (implicit slot scheduling)	None	No

Compared to the LPL protocol, Crankshaft's delivery ratio starts to drop at lower message rates because the per-node receive bandwidth is limited to one receive slot per frame. Therefore, the Crankshaft protocol cannot achieve the high delivery ratios of LPL and SCP-MAC at high message rates. The restricted receive bandwidth also guarantees high energy-efficiency, with the Crankshaft protocol consuming a factor of 3.5 less energy than SCP-MAC. There are two factors which contribute to the energy efficiency: firstly, because only a subset of the nodes is awake in each slot overhearing is reduced. Secondly, contention is reduced by the static slot allocation.

LMAC suffers from the need to assign a contention-free slot to all nodes in the network resulting in network congestion from the low per-node bandwidth. Therefore, the LMAC protocol delivers both a low delivery ratio (even at low message rates) and a high latency. The energy consumption remains nearly constant, because the LMAC protocol already saturates at low message rates.

Finally, T-MAC suffers from the aggressive sleep policy that causes nodes to go to sleep too often, which hinders throughput. It, however, achieves a better latency than Crankshaft and LMAC, because the per-node bandwidth limitations of the latter two are too restrictive. The aggressive sleep policy does provide low energy consumption.

3.4   Evaluation Summary

Table 1 is a summary of the WSN MAC protocol review. Both the numerical and qualitative evaluation of the stat-of-the-art, highlight the fact that none of the leading WSN MAC protocols satisfy all the of the active flow control application. The numerical results suggest that SCP-MAC may offer the best trade-off between system spectral efficiency and energy efficiency. However, these results were obtained for a low density network, with a single cluster per tier, and no simultaneous communication at higher and lower tiers, resulting in no inter-cluster interference. This is vastly different to the proposed active aircraft sensor deployment, in which as discussed, the SCP-MAC is expected to perform poorly due to its lack of receiver interference awareness and wasteful contention overhead. Therefore, the focus of future work will be to design and evaluate new protocols that satisfy all the requirements of the proposed application. The dependence of the MAC on interference awareness, network topology and traffic generation and propagation patterns suggest a cross-layer design methodology encompassing physical layer (modulation/coding, channel estimation), MAC and routing algorithms.

4   Routing Protocols

WSN nodes are small, wireless and battery-powered. They can store a limited amount of energy in their batteries, which they must consume extremely efficiently. Because of this, their processing, storage and communication capabilities are limited. Due to the large number of nodes in each of the large number of network deployments, it is not possible to build a global addressing scheme for WSN. Almost all WSN applications require data to flow from multiple sensor nodes towards a few sinks, where generated data presents significant redundancy since multiple sensors within a region will record mostly the same data within the same time frame. In short, WSN are a very special form of self-organising ad hoc networks, which require special design under the consideration of the following issues [12]:

- Energy efficiency;
- Data processing and storage;
- Communication range and bandwidth;
- Topology and lack of global addressing;
- Data redundancy and flow type;
- Application requirements;
- Scalability.

The constraints related to the physical world are common to all types of sensor applications, so that research on physical and link layers usually focus on system-level energy awareness. When designing at the network layer, on the other hand, application requirements need to be considered in the design process to ensure efficient resource management. With respect to routing, the main aim is to set up and maintain energy-efficient routes to deliver sensor data to sinks (and, eventually, to a central controller) in a reliable manner while keeping the network up and running as long as possible [13]. In this regard, energy efficiency can be considered as the primary design objective, the common denominator of all WSN routing approaches, which relates to both the selection of the routes as well as the overhead of routing.

Secondary aspects in WSN routing, such as stability and dependability of the routes, are also very important and need to be considered as such in accordance with the application requirements and, of course, without forgetting the primary objective of energy efficiency. Multi-path routing for load and energy balancing can improve the resilience of the WSN. Secondary (or stand-by) paths can help the network find better trade off opportunities between robustness and energy efficiency. On the other hand, routing table sizes should be kept small since WSN nodes have limited memory. Routing protocols exploiting data redundancy can have a clear advantage in terms of energy and bandwidth efficiency.

In this section, we first summarise the design considerations for Active Aircraft. Then, we broadly classify the routing protocols designed for WSN and compare the common characteristics of the different types of protocols to the design consideration. Based on this comparison, we then review some of the more promising routing protocols from the literature. Using the performance metrics of Active Aircraft, these routing protocols are evaluated, pointing at their advantages as well as disadvantages, such that necessary improvements can be made in the next stages of protocol development.

4.1   Design Considerations for Active Aircraft Routing

Considering the Active Aircraft scenario, several assumptions need to be made on the topology of the network, flow of information, amount of data, energy and QoS requirements of the nodes. Once these assumptions are made, a requirement specification can be given and compared to the classification of routing protocols presented above.

4.1.1 Network Dynamics

The sensor nodes will be stationary. Most probably they will have a grid-like topology along the surface of the wings (and the body) of the aircraft. This will make it relatively easy to define routing paths and, if necessary, map geographical regions (relative to the aircraft) to network addresses in a deterministic way.

4.1.2 Node Deployment

Manual node placement will be possible. However, the sensor nodes will be wireless, which means that they will be battery-powered. Since many sensors will experience temporary and permanent communication problems due to the extreme environmental conditions, self-organisation will also be needed in the network.

4.1.3   Data Delivery Model

Most of the flow of information will be periodic. The measurements on temperature, air pressure and other environmental conditions aim at observing the status of the aircraft continuously and adapting its behaviour accordingly. To a relatively small extent, event-driven information gathering can be required to enable the central control system to react to unexpected and rare events.

4.1.4   Service Classes

The Active Aircraft can broadly be distinguished into monitoring and control applications. The former is based on observing the long-term status and is therefore tolerant to delay and loss. The latter, however, requires short-term and accurate information to take the most appropriate action and is therefore sensitive to the mentioned criteria. Thus, two service classes can be defined to represent best-effort and real-time data traffic within the context of Active Aircraft to support the QoS requirements of both applications efficiently. The control application is assigned the higher priority service class than the monitoring application and has precedence over it in terms of resource allocation.

4.1.5   Node Capabilities

It will be possible to install a relatively small number of sinks with unlimited energy and high computational power to the WSN. Being considerably more powerful, the sinks can be configured as gateways to the wired or wireless infrastructure backbone network. They can take over heavy duties such as collecting, processing and interpreting data. However, energy considerations will be in charge for the rest of the WSN.

4.2   Classification of Routing Protocols for WSN

Many algorithms have been proposed for routing data in WSN, attempting to consider one or more of their characteristic differences which make the adaptation of existing wired, wireless and even ad hoc routing schemes infeasible. Most of these routing protocols can be broadly classified as follows [14]:

- Data-centric protocols, which are query-based and depend on the naming of the data.
- Hierarchical protocols, which aim at clustering the nodes and aggregating the data to save energy.
- Location-based protocols, which utilise the position information to direct the data to a desired region.
- QoS-aware protocols, which try to meet some QoS requirements such as delay, loss and throughput.

4.2.1   Data-centric Protocols

For many WSN applications, the main task is to observe a predefined phenomenon in a specified region. To achieve this objective, it may not be necessary to query each single sensor node in the network throughout the lifetime of the application. It is rather preferred to define the properties of the data identifying the phenomenon, specify the region of interest and let the WSN do the rest. Due to the lack of global addressing and the random deployment of sensor nodes, however, it is hard to select a specific set of sensor nodes to be queried. This leads us to data-centric routing, where the sink sends queries to certain regions and waits for data from the sensors located in the selected regions. Thus, data-centric protocols are able to query a set of sensor nodes with respect to the naming of the desired data. Since data is being requested through queries in this type of protocols, the attribute-based, unified naming of the phenomenon under observation is crucial to specify the properties of data. Flooding and gossiping are the simplest types of data-centric protocols.

Sensor Protocols for Information via Negotiation (SPIN) is the first data-centric WSN protocol [15], to be followed by Directed Diffusion (DD) [16]. Many other protocols have been proposed later, either based on DD or following a similar concept.

As an on demand query schedule, data-centric routing does not need to keep global network topology information. Due to the excessive number of queries generated, however, it cannot be used in applications requiring continuous (or periodical) data delivery to the sink, such as environment monitoring. Moreover, the naming mechanism is application-specific and must be defined in advance, which results in poor reusability. Finally, they flood the network with queries, which results in communication overhead and time delay.

4.2.2   Hierarchical Protocols

Similar to the conventional networking design objectives, scalability is one of the major attributes for WSN. A flat network topology can cause the gateway node to become overloaded with the increase in sensor density, which causes delay in communication and data loss. To allow the system to cope with additional load and to be able to cover a large area of interest without degrading the service, hierarchical routing protocols form clusters to organise sensor nodes into. Nodes are encouraged to take part in multihop communication within clusters, which allows them to transmit messages using less power. The cluster heads aggregate and relay data to the sink. This approach decreases the energy consumption of single sensor nodes as well as the number of transmitted messages to the sink.

Low Energy Adaptive Clustering Hierarchy (LEACH) is one of the first hierarchical routing approaches for WSN [17]. The idea proposed in LEACH has been used by many other hierarchical routing protocols, such as Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [18] and Threshold-sensitive Energy-Efficient Sensor Network Protocol (TEEN) [19]. A self-organising protocol (SOP) and a routing architecture that requires the addressing of each sensor node is proposed in [20]. More recently, the minimum-energy spanning tree for efficient routing (MESTER) [21] is developed to address, in addition to energy efficiency and network lifetime, the applications' throughput and delay requirements.

Hierarchical routing can progressively prolong the network system lifetime because of its dynamic cluster operation. In addition, these protocols are distributed and require no global knowledge on the network. However, dynamic clustering incurs extra overhead to the network, such as the changing operation of cluster head.

4.2.3   Location-based Protocols

The idea behind the location-based protocols is to use an area instead of a node identifier as the target of a packet. Any node that is positioned within the given area will be acceptable as a destination node and can receive and process a message. In the context of WSN, such routing is evidently important to request sensor data from a desired region. Since there is no addressing scheme for WSN like that of the Internet Protocol (IP) and nodes can be spatially distributed in a rather large region, location-based protocols can route data in an energy-efficient way using the location information. For instance, queries can be diffused only to particular regions to be sensed, which will eliminate the number of unnecessary transmissions significantly.

There are a number of location-based protocols designed primarily for mobile ad hoc networks (MANET), which are also applicable to sensor networks. Three main protocols of this category are the Small Minimum Energy Communication Network (SMECN) [22], Geographic Adaptive Fidelity (GAF) [23] and Geographic and Energy-Aware Routing (GEAR) [24].

Location-based routing protocols perform well when the density of network is high. However, their performance is poor when the network deployment is sparse, and there is no data aggregation and further processing by a header node.

4.2.4   QoS-based Protocols

QoS-based protocols consider end-to-end delay, throughput and data loss. In some approaches such as maximum lifetime energy routing and maximum lifetime data gathering, route setup is modeled and solved as a network flow problem. In real-time applications including target tracking in battle environments and emergent event triggering in monitoring applications, QoS-aware protocols consider end-to-end delay requirements while setting up the paths in the sensor network.

Currently, there is very little research about QoS-aware protocols for WSN, among which are examples like Sequential Assignment Routing (SAR) [25], an energy-aware QoS routing protocol (EQR) for wireless sensor networks [26] and a stateless protocol for real-time communication in sensor networks (SPEED) [27].

QoS-aware routing algorithms can provide good QoS performance resulting from their design goal. However, the most important requirement in WSN is energy efficiency, so this approach should be considered with other energy-efficiency metrics at the same time.

4.3   Review of WSN Routing Protocols with Potential Applicability

Based on the assumptions summarised in Section 4.1 and the classification presented in Section 4.2, Table 2 maps the requirements of Active Aircraft to the protocol characteristics and shows which of these characteristics are desired and which are rather not. In this section, we will revisit the WSN routing protocols and emphasise the ones which have a higher potential of matching the application requirements of Active Aircraft.

Our goal is to identify the WSN routing protocols which satisfy a sufficient subset of requirements set by the Active Aircraft. In doing this, we need to check the correlation between the protocol characteristics and our application requirements. On the other hand, we also need to avoid the ones with unnecessary features, which would cause inefficiencies in resource management in the network. Table 3 visualises the classification of the various protocols mentioned in the preceding section once again according to their characteristics. A row showing the data aggregation capability of the protocols is also inserted to the four characteristics. This capability is useful in terms of bandwidth as well as energy efficiency for applications which produce high volumes of redundant data. The dark rows of the table show the characteristics desired by our application scenario. The bottom row shows our evaluation summary in terms of the protocol's suitability to our purposes. One star is added to the aggregate potential value for each desired characteristic, whereas one is subtracted for each undesired characteristic to represent its negative effect on the overall system performance.

Table 2: Evaluation of the different protocol characteristics with respect to Active Aircraft application requirements.

Protocol Characteristics	Required?	Reasoning for Active Aircraft Applications
Data-centric	✖	Most of the information gathering will be periodic. A data-centric approach would cause too much message overhead to query data which can be easily sent automatically with a predefined frequency.
Hierarchical	✔	The amount of the data to be gathered will be high. Data aggregation will be needed to save bandwidth and energy. Multi-hop communication will be encouraged to limit the transmission power of the sensors.
Location-based	✖	Sensor nodes will be fixed on the skin of the aircraft in advance. A grid-like network topology will enable the routing protocol to distinguish the sensor regions without the assistance of geographical positioning.
QoS-aware	✔	Distributed local control requires data accuracy. Centralised global control necessitates low latency. Reliability, delay and loss are important QoS factors for control commands.

Table 3: Summary of the routing protocol classification for WSN.

Protocol Characteristics	SPIN [15]	DD [16]	LEACH [17]	PEGASIS [18]	TEEN [19]	SOP [20]	MESTER [21]	SMECN [22]	GAF [23]	GEAR [24]	SAR [25]	EQR [26]	SPEED [27]
Data aggregation	★	★	★	★	★	★	★						
Data-centric	★	★			★								
Hierarchical			★	★	★	★	★		★			★	
Location-based								★	★	★			★
QoS-aware											★	★	★
Aggregate Potential Value	–	–	(★★)	(★★)	(★)	(★★)	(★★)	–	–	–	(★)	(★★)	–

As we can see from the table, none of the protocols covers all three of the desired characteristics, which means that none of them is perfectly suitable for Active Aircraft. However, there are five protocols fulfilling 2 of the 3 requirements. These are LEACH, PEGASIS, SOP, MESTER and EQR, which are summarised below.

4.3.1 Low-Energy Adaptive Clustering Hierarchy (LEACH)

LEACH [17] is one of the most popular hierarchical routing algorithms for WSN. The idea is to form clusters of the sensor nodes based on the received signal strength and use local cluster heads as routers to the sink. This saves energy since long-distance transmissions are only made by the cluster heads rather than all sensor nodes. The optimal number of cluster heads is estimated to be 5% of the total nodes. Data processing and aggregation are done locally within the cluster. Cluster heads change randomly over time in order to balance the energy dissipation of nodes.

LEACH achieves over a factor of 7 reduction in energy dissipation compared to direct communication and a factor of 4–8 compared to the minimum transmission energy routing protocol [14]. Dynamic clustering increases the lifetime of the system. LEACH is completely distributed and requires no global knowledge of network. However, LEACH uses single-hop routing where each node can transmit directly to the cluster head and the sink. Therefore, it is not applicable to networks deployed in large regions. Furthermore, the idea of dynamic clustering brings extra overhead, e.g. head changes, advertisements etc., which may diminish the gain in energy consumption.

4.3.2 Power-Efficient Gathering in Sensor Information Systems (PEGASIS)

PEGASIS [18] is an improvement to LEACH. Rather than forming multiple clusters, PEGASIS forms chains from sensor nodes so that each node transmits and receives from a neighbour and only one node is selected from that chain to transmit to the sink. Received data is aggregated at each node and eventually sent to the sink. The chain is constructed in a greedy way. Different than LEECH, PEGASIS uses multi-hop routing.

PEGASIS outperforms LEACH by about 100–300% for different network sizes and topologies. This performance gain is achieved through the elimination of the overhead caused by dynamic cluster formation and the decreasing of the number of transmissions via data aggregation. However, PEGASIS introduces excessive delays for distant nodes on

the chain. In addition, the single leader can become a bottleneck. Thus, hierarchical-PEGASIS [28] is developed, which aims at decreasing this delay through simultaneous transmission of data messages and proposes a solution to the data gathering problem by considering an energy x delay metric.

4.3.3 Self-Organising Protocol for Sensor Nodes (SOP)

In the SOP architecture [20], a group of sensors, which can be either stationary or mobile, probe the environment and forward the data to designated set of nodes that act as routers. Router nodes are stationary and form the backbone for communication. Collected data are forwarded through the routers to more powerful sink nodes. Sensor nodes are identifiable through the address of the router node it is connected to. The routing architecture is hierarchical where groups of nodes are formed and merge when needed. The algorithm for self-organising the router nodes and creating the routing tables consists of discovery, organisation, maintenance and self-reorganisation phases.

Since sensor nodes can be addressed individually in the routing architecture, the proposed algorithm is suitable for applications such as parking-lot networks where communication to a particular node is required. The major advantage of the algorithm is the small cost of maintaining routing tables and keeping routing hierarchy strictly balanced. Moreover, the energy consumed for broadcasting a message is less than that consumed in SPIN due to the broadcast trees utilized in the algorithm. The disadvantage is in the organization phase of algorithm, which is not on-demand, therefore introducing extra overhead. Another possible problem is in case of hierarchy forming when there are many cuts in the network. This is expensive since network-cuts increase the probability of applying reorganisation.

4.3.4 Minimum Energy Spanning Tree for Efficient Routing (MESTER)

MESTER employs a centralised algorithm to manage the network topology, calculate the routing paths and schedule the data collection, which is run by the sink node and broadcast to the sensor nodes [21]. The aim of the protocol is to optimise the network with regard to throughput and delay in addition to conventional WSN performance metrics such as energy efficiency and network lifetime.

The algorithm consists of three phases. In the first phase, a minimum spanning tree (MST) is calculated by the sink node by choosing a sensor node randomly as the root and applying Prim's algorithm with the communication distance used as the link weight. In phase two, a leader node is selected by the sink among the sensors based on their residual energy and communication pairs are formed for packet delivery towards the leader. The propagation of data is scheduled in time slots and a communication round is completed when aggregated sensor data is forwarded from the leader to the sink. In the third phase, the sink broadcasts the time schedule, which is followed by the sensor nodes. Phases two and three are repeated after the completion of each round, whereas the algorithm returns to the first phase for MST recalculation if the topology changes (i.e. when a node dies).

MESTER decouples tree generation and energy load balancing, thus achieving a low computational complexity. However, it works better with balanced trees, where nodes have approximately the same number of children as well as the same hop distance to the selected leader. To improve the protocol on this point, the shortest hop routing tree (SHORT) algorithm is proposed [29], where the scheduling of transmissions is based on the distance from the individual sensors to the leader. In other words, the sensor node farthest from the leader is allocated the first time slot. In addition, leader selection is not random as in MESTER but based on the ratio of the remaining energy to the distance to the sink.

4.3.5 Energy-Aware QoS Routing (EQR)

The EQR protocol [26] finds a least cost and energy-efficient path that meets certain end-to-end delay requirements during the connection. The link cost is a function of the nodes' energy reserve, transmission energy, error rate and other communication parameters. In order to support both best effort and real time traffic at the same time, a class-based queuing model is employed, which allows service sharing for real-time and non-real-time traffic. The protocol finds a list of least cost paths by using an extended version of Dijkstra's algorithm and picks a path from that list which meets the end-to-end delay requirement.

Simulation results show that the proposed protocol consistently performs well with respect to QoS and energy metrics. However, the service sharing parameter has initially the same value for all the nodes, which does not provide flexible adjusting of bandwidth sharing for different links. Thus, the protocol is extended [30] by assigning a different value for each node in order to achieve a better utilisation of the links.

4.4 Numerical Comparison

MESTER is compared via simulation to PEGASIS, the power-efficient data gathering and aggregation protocol (PEDAP) and its power aware version (PEDAP-PA) [21]. To investigate the impact of network size on performance, two networks of 50 and 100 sensor nodes are considered, where the nodes are randomly distributed in a 100×100 m^2

square field. The sink node is located outside this sensing field at the coordinates (50 m, 150 m). The sensor nodes are able to adjust their transmission power to minimise interference and ensure error-free packet transmissions. For the sake of generality and accuracy, the following results are the average of five simulations with identical parameters for different randomly-distributed network topologies of the same size and in the same field. In this section, we summarise the results presented in [21] for 100 nodes. The next step of our research is to extend this evaluation to other candidate routing protocols to make a selection between them and identify the issues that need improvement.

Figure 10 shows the network lifetime as a function of node deaths in a network of 100 nodes [21]. MESTER performs comparably well against PEDAP and PEDAP-PA with a much lower computational complexity. It can also be seen that the MST-based schemes outperform the chain-based PEGASIS protocol. Compared with PEDAP and PEGASIS, PEDAP-PA and MESTER have much longer FND lifetimes as a result of their energy load balancing mechanisms. Specifically, the approach of re-calculating MST in PEDAP-PA is more effective for load balancing than the mechanism of leader switching in MESTER, but the former requires about n (network size) times more computation time than the latter. The lifetime curves for PEDAP and MESTER have an obvious "step" at the beginning of network operation. This phenomenon implies several high-degree nodes in the MST drain off their energy and die at almost the same time.
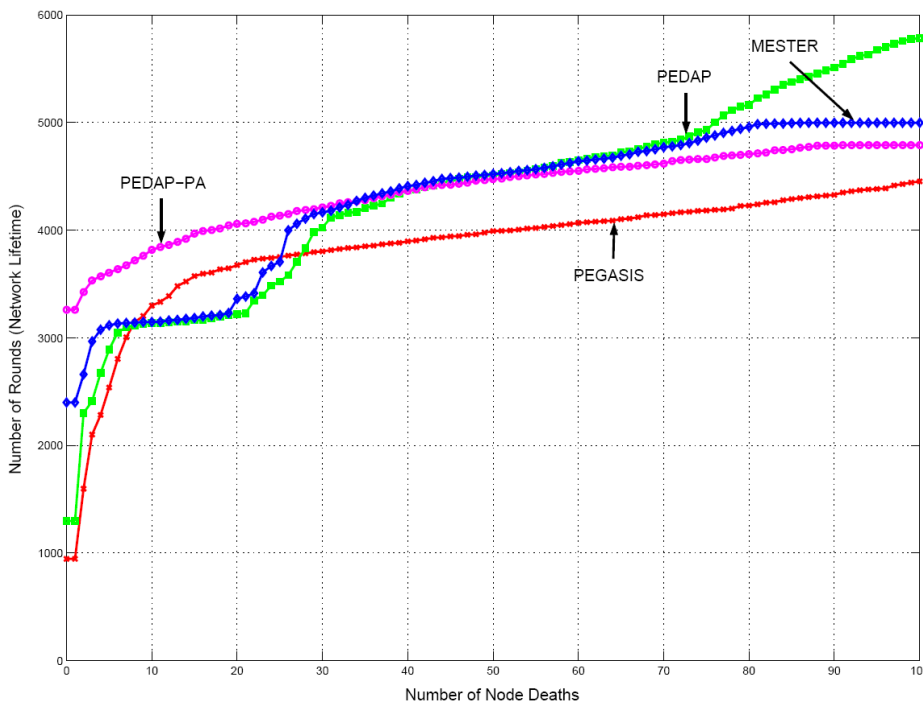

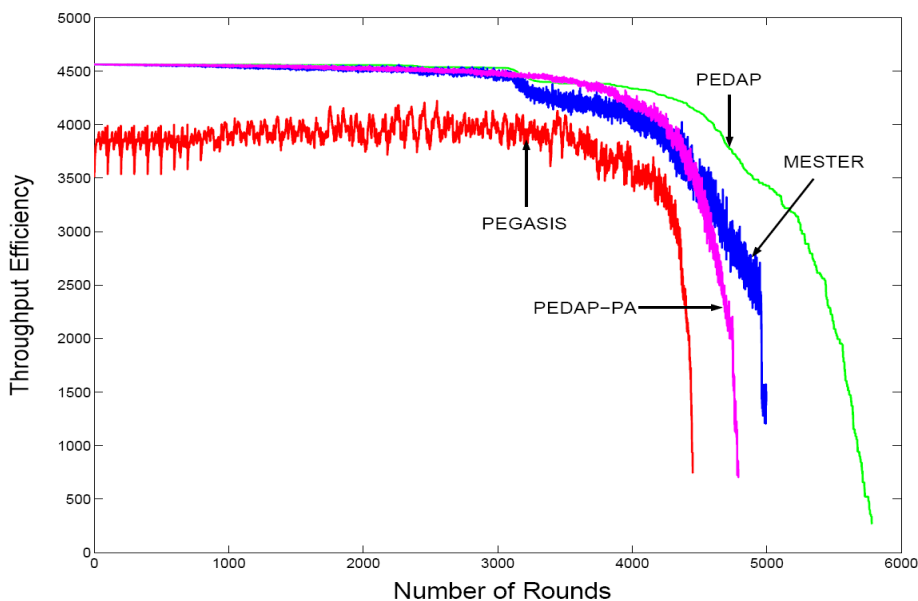**Figure 10: Comparison of the network lifetime performance. [21]**

Figure 11: Comparison of the throughput efficiency performance. [21]

Table 4: Comparison of MESTER to other protocols. (FND: first node dies, HND: half of nodes die, LND: last node dies) [21]

Performance Metrics		PEGASIS	PEDAP	PEDAP-PA	MESTER
Energy Efficiency (×10^{-3}J per data collection round)		22.40	17.20	20.70	**19.90**
Network Lifetime (# of data collection rounds)	FND	945	1297	3260	**2398**
	HND	3992	4508	4473	**4522**
	LND	4453	5783	4791	**4998**
Delay (# of slots for each data collection round)	mean	66.02	14.10	16.19	**15.80**
	std	18.95	-	2.58	**-**
Energy × Delay (J × slot)		1.58	0.27	0.34	**0.32**
Throughput (# of data packets in each data collection round)		**86.70**	**75.28**	**91.29**	**85.87**

Combining energy efficiency and throughput, the new concept "throughput efficiency" is a precise performance metric to measure a routing scheme's capability of collecting more data at less energy cost in each round. Thus, Figure 11 shows the performance of throughput efficiency of the protocols over the network lifetime [21]. MESTER and PEDAP-PA are very similar in terms of throughput efficiency. The smoothness of the curves, which is a good sign for the stability of the protocol in terms of throughput and unit energy consumption, depends on how much a role the communication distance plays in the selection of the leader. PEDAP selects the leader (i.e. the root of the MST) purely according to each node's distance to the sink, thus offering the smoothest curve. Both MESTER and PEDAP-PA consider each node's remaining energy and distance to the sink in the selection of leader, so the smoothness of their throughput efficiency curves is in between that of PEDAP and PEGASIS.

Other main results against different performance metrics are summarised in Table 4 [21]. In general, MESTER offers moderate performance between that of PEDAP and PEDAP-PA, whereas it outperforms PEGASIS. PEDAP has the lowest energy consumption in each round and, therefore, achieves the longest LND lifetime. However, its throughput performance, which is proportional to the number of alive nodes in each data collection round, is not as high as the others. As to the average delay for data collection in each round, PEGASIS offers about four times larger delay values for 100-node networks compared with those of MST-based schemes. This is because an MST has a more dispersed distribution of node degrees than a chain and is therefore more efficient in generating parallel communication pairs and reducing delay. Subsequently, the MST-based MESTER, PEDAP and PEDAP-PA achieve a much better "energy × delay" performance than PEGASIS, showing a good balance between energy efficiency and delay.

4.5   Evaluation Summary

In light of the evaluation of the protocol characteristics according to the Active Aircraft application requirements, only a few of the state-of-the-art WSN routing protocols provide a solution which is close enough to the right combination. It is obvious that a protocol showing all of the above characteristics is not necessarily optimal for the Active Aircraft scenario since this protocol would be overqualified, which would lead to inefficiencies in terms of computational complexity and energy consumption, probably not possible to be eliminated by simply turning off the unwanted features. It is more desirable to select a protocol with a subset of design features closest to our requirements from the beginning and build our solution upon that protocol by enhancing it according to our needs. As the next step of this project, we will evaluate the candidate routing protocols further to find out whether they can be improved and become applicable to Active Aircraft. Based on this evaluation, we will then design and develop our solution to the Active Aircraft routing challenge.

5   Summary and Conclusions

This report presents a review of the state-of-the-art medium access control and routing protocols for WSAN. A topological design is introduced as part of the solution for decentralised local and centralised global control problem as potential for the Airbus/ESPRC Active Aircraft Project. Following this, candidate protocols for the implementation of the communication algorithms are classified and evaluated.

In order to proceed in our research on MAC and routing protocols, we made several assumptions on application requirements, which, to the best of our knowledge, are sufficiently realistic. Nevertheless, the refinement and optimisation of our solutions depends heavily on the validation of our assumptions on Active Aircraft as well as on a number of environmental conditions. Therefore, the following open issues need to be addressed by Airbus.

- We need wireless channel characteristics and models in and especially exterior to the aircraft. Airborne propagation conditions might differ from the conditions on the gound significantly, particularly due to the effect of wind and the lack of reflection. Therefore, it is essential that we have results of channel measurements, statistic data analysis and approximation. We also need to know whether time synchronisation by global positioning system (GPS) signals could be an option with regard to the systems on the aircraft. In some cases, regulations prevent the use the GPS data.

- We need information on the types of data being sensed, such as air pressure, wind speed, temperature etc. used to determine the current skin friction drag. We are also interested in the traffic patterns generated as a result of the sensing activity. In other words, we'd like to know the size, frequency and priority of the generated data. We will use this information to optimize our communication algorithms and data aggregation methods. We will also define the design parameters and capabilities of the sensor/actuator devices accordingly. Examples of these parameters are signal processing, storage, communication range, energy consumption, and reliability.

- What are the technical requirements of active control approaches in terms of accuracy, robustness and sensitivity to delay/throughput performance of the network?

As mentioned previously, resource efficiency plays an important role in the design of application-specific protocols at the network layer. As an extension to our ongoing work on MAC and routing protocols, we are also investigating cross-layer MAC and routing solutions that need to be developed for integrated resource management.

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