Implementation of a Wireless Mesh Network of Ultra Light MAVs with Dynamic Routing

Alberto Jimenez-Pacheco  
*Laboratory of Mobile Communications, EPFL, Switzerland*  
alberto.jimenez@epfl.ch

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*Joint work with:* Denia Bouhired, Yannick Gasser, Jean-Christophe Zufferey,  
Dario Floreano and Bixio Rimoldi
Outline

1. Introduction
2. Flying Platform
3. Communication Systems and Dynamic Routing
4. Experimental results
5. Conclusions and future work
**SMAVNET**: Swarm Micro Air Vehicle NETwork

- **Framework**: Swarming network of unmanned micro air vehicles for deployment in outdoor areas and challenging terrain:
  - Disaster areas of difficult access
  - Urban environments

  ⇒ Fast deployment + high maneuverability + no pre-existing infrastructure

- **Goal**: To improve the wireless communications
  - Extend communication range
  - Avoid obstacles (nLOS communication)

- **Challenge**: system must cope with
  - Fast variability of the wireless channel
  - High mobility of the MAVs

- **Proposed solution**: WiFi + dynamic routing with OLSR (with link quality extensions)
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Flying Platform

- Built on expanded poly-propylene
- Total weight \(\approx 450\) g
  - Very small inertia
  - Safe for third parties
- Payload \(\approx 150\) g
  - Tight constraints for communication equipment: weight, power consumption, computing power
- Propelled by DC electrical motor in the rear end
- Elevons: two control surfaces that serve as combined ailerons and elevators
- LiPo battery (\(\approx 60\) min autonomy)

Drone cruise speed \(\approx 10\) m/s
Can operate in light breeze, with wind speeds up to 7 m/s
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![Diagram of the flying platform](image)
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Flying Platform: Electronic Systems

Two electronic subsystems integrated in the EPP body (surrounded with protective foam):

**Autopilot**

- Uses a dedicated DSP to implement flight control strategies
- Integrates a GPS unit, pressure sensors and inertial sensors
- It enables autonomous take-off, followed by way-point navigation at preset altitudes, and autonomous landing

**Embedded Computer**

- Responsible for mission control: data logging, WiFi communications, camera control, etc
- Gumstix Overo-Tide COM (Computer on Module)
  - ARM arch @720 MHz, OS Ångström Linux, 4.3 g, 58 × 17 × 4.2 mm
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Control Link
- Point-to-multipoint topology
- Navigation instructions from control ground station to each MAV
- Based on an XBee Pro radio (IEEE 802.15.4)
- ISM Band 2.4 GHz (channel bandwidth = 5 MHz)
- Long range (1.6 Km), limited delay, high reliability, small bandwidth (max 250 Kbps)

Data Link
- Mesh topology (multi-hop, relaying, ferrying)
- Based on WiFi (IEEE 802.11)
- ISM Bands, 2.4 GHz and 5 GHz (channel bandwidth = 20/40 MHz)
- Higher data rates, required for multimedia applications
- But reduced communication range (≈ 400 m in free space)
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IEEE 802.11 WiFi communications

Pros
- Operate in the freely usable ISM bands
- Inexpensive COTS components
- Reduced weight, dimensions and power consumption
- Support for ad-hoc mode

Cons
- Designed for indoor, static environments (low Doppler)
- Limited Linux support
- Ad-hoc mode offers no support for routing
  - Overcome by using routing protocols on top of the WiFi stack
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Optimal Link State Routing (OLSR)

Why OLSR for dynamic routing?
- Proactive algorithm (continuously maintain routes to all destinations)
  - High mobility of the MAVs, rapidly changing channel
- Operates at OSI layer 3 (MAC and PHY agnostic protocol)
  - No need to modify drivers
  - Daemon modifies kernel routing tables in a transparent way
  - Easier to simulate (ns2, core, etc)
    - compared to routing protocols operating at OSI layer 2
- OLSRd is an open source project under a BSD-style licence
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Optimal Link State Routing (OLSR)

How does it work?

- **HELLO packets**: periodically broadcast for link quality sensing
  - Each node builds list of neighbours and associated link qualities
- **TC (Topology control) messages**: used by nodes to declare their list of neighbours
  - Propagate topology information of the network to all member nodes
  - Used special nodes MPR (Multi-Point Relays) to forward control traffic intended for diffusion in the entire network
- Dijkstra’s algorithm to select minimum cost routes
- *Every* node keeps a table with the next hop for the routes to *all other* nodes in the network
- Topology database must be kept synchronised across the network!
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ETX Metric (Expected Transmission Count)

- **ETX**: expected number of MAC layer transmission needed to successfully deliver a packet over a link
  - **LQ** (Link Quality): fraction of HELLO packets correctly received from a neighbour in a sliding time window
  - **NLQ** (Neighbour Link Quality): probability that a HELLO message that we send is correctly received by that neighbour
  - Roundtrip: \( p = LQ \times NLQ \): transmission successfully received and correctly acknowledged
  - Number of trials before successful transmission: geometric RV with parameter \( p \) and mean

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ETX = \frac{1}{LQ \times NLQ}
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- For multi-hop routes, the aggregate ETX is the sum of the ETX of each link in the route
- Minimizing aggregate ETX \( \equiv \) Find routes of maximum throughput
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OLSR for MANETs

- OLSRd does not specifically take into account the mobility of the nodes
- But if it is configured to propagate route metrics quickly, then ETX will choose good routes in spite of mobility
- Configuration parameters should be tuned according to node speed and expected mobility patterns
  - HELLO interval
  - TC interval
  - Ageing parameter
- Fundamental trade-off: accuracy of link measurements ⇔ responsiveness to mobility
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Experimental results - Throughput vs Distance

1-hop scenario

Throughput vs Distance plot for 1-hop scenario

Theoretical Max 13 Mbps

2-hop scenario

Throughput vs Distance plot for 2-hop scenario

Theoretical Max 6.5 Mbps

Fixed ground station and one MAV that flies back and forth in straight line

Relay MAV describes circular waypoint centered halfway between ground station and destination MAV.

Relaying enforced

⇒ Max throughput halved, but extended range
Experimental results - Throughput vs Distance

1-hop scenario

Throughput vs Distance

Distance [m]

Throughput [Mbps]

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2-hop scenario

Throughput vs Distance

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1-hop scenario

- Orientation of the MAV affects performance
- Short range ($d < 300 \text{ m}$): little sensitivity to orientation
- Long-range ($d > 450 \text{ m}$): lost connection
- Mid-range ($300 < d < 450 \text{ m}$): inbound rate higher than outbound rate
- Motor/electronics shadow communication path?

- Ground station at origin of coordinates
- Several circular waypoints of radius 50 m
- Center in straight line, progressively further from ground station
- Diameter of blue data points $\propto$ throughput

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3 nodes, dynamic routing with OLSRd. Relay status and trajectory followed by destination MAV

- Short range \((d < 400\, m)\): strong 1-hop connection
- Long range \((d > 600\, m)\), outbound: stable 2-hop connection
- Mid-range \((400 < d < 600\, m)\): jittery relay status, sensitive to orientation

Relaying MAV describes circular way-points, radius 50m, center half-way between ground station and that of way-points described by destination MAV.
Experimental results - Relay status

3 nodes, dynamic routing with OLSRd.
Relay status and trajectory followed by destination MAV

- Short range \((d < 400 \text{ m})\): strong 1-hop connection
- Long range \((d > 600 \text{ m})\), outbound: stable 2-hop connection
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Relaying MAV describes circular way-points, radius 50m, center half-way between ground station and that of way-points described by destination MAV.
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- Designed single-frequency MANET of ultra-light MAVs and ground nodes
- ISM band, standard technologies, COTS components, open source software
  - Ideal for economic, quick, temporary deployment - anywhere
- Demonstrate feasibility of using dynamic routing with OLSRd to cope with the high mobility of the MAVs and harsh wireless channel
- Characterised the effects of distance and aircraft orientation on end-to-end achievable throughput and routing decisions
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  - Not only distance but orientation impact performance (unless MAVs are within short range)
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- Costly and time-consuming experimental testing
  - Need to combine with simulation/modelling tools
  - Current work: Flight simulator + Network simulator (CORE/EMANE)
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- Exploit interface between autopilot and embedded computer
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Questions?
Extra Slides
IEEE 802.11 WiFi communications

WiFi card - Sparklan WUBR507N

- Multi standard (802.11 a/b/g/n), dual-band model (Ralink chipset)
- Very flexible Linux driver, access to detailed PHY configuration
- $65 \times 25 \times 2 \text{ mm}, 7 \text{ g} \Rightarrow \text{ minimal impact on aerodynamics}$

Configuration

- Driven by robustness
- 802.11n in 5 GHz band, MIMO with 2 antennas (Alamouti, no BLAST)
- MCS (Modulation and Coding Scheme): QPSK, $13 \text{ Mb/s}$ (fixed, data rate switching disabled), rate 1/2 channel coding, long GI
- “Greenfield” mode - all nodes in the network operate in 802.11n (and with exactly same settings)
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Intra- and Inter-flow interference

Nodes contend for bandwidth with:
- Other nodes in the same communication path
- Nodes in geographic proximity belonging to other paths

- **Intra-flow** interference reduces the throughput with every node added in multi-hop chain \( \Rightarrow \)
  Can be avoided using multiple wireless interfaces on each node (multi-frequency network)
  - Increased weight, reduced autonomy of MAVs
  - Complicate optimization of dynamic routing

- **Interflow** interference: routing protocol needs geographic information to avoid it
Intra- and Inter-flow interference

Two communication flows: \( S_1 \rightarrow D_1 \) and \( S_2 \rightarrow D_2 \)

**Intra-flow**: \( S_1 \rightarrow X_1 \) and \( X_2 \rightarrow D_1 \), or \( X_1 \rightarrow X_2 \), but not both simultaneously

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Pros and Cons of the ETX metric

Advantages

- Maximize throughput taking into account packet loss of the links
- Handles asymmetric links
- Accounts for *Intra-flow* interference
  - Summation of ETX in multi-hop routes reflects that a relay cannot receive data from previous hop and forward it to next at the same time
- Decreases energy consumed per packet

Criticism

- ETX does not consider that links may have different PHY rates
  - Corrected by ETT metric (Expected Transmission Time)
- ETX estimations use single (small) size for the probe packets
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