Development of UAV Wireless Communication Systems in NICT

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National Institute of Information and Communications Technology (NICT)
Contents

- Background of UAV Wireless Communication Systems
- Development of UAV-based wireless relay network system in natural disasters
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Background-1

- Unmanned aircraft systems (UAS) or drones have received a lot of attention in recent years in the world for several applications
  - wind and flood damage and fire, monitoring and observation, deliveries of goods

- Reliability of communication and the safe operation of UAS is becoming urgent need with the expansion of the needs of the UAS.

- The World Radiocommunication Conference (WRC)
  - WRC 2012 (WRC-12) decided the allocation of the frequency band 5 GHz band (5030 MHz ~ 5091 MHz) for the UAS Control and Non-Payload Communications (CNPC) Link.
  - Toward the next WRC (WRC-15), allocations of the Ku/Ka frequency bands to establish a communication link between UA and remote pilot through satellite have being discussed

-> Research and development of interference mitigation techniques has become a pressing issue.

We report the development of a UAV-based wireless relay network system and an on-board Ka band tracking antenna to satisfy the requirements of realization of UAS CNPC link between UA and satellite.
Target UAs of this research

Small type UAs

Medium and Large type UAs
Require Beyond-Line-of-Sight (BLOS) operations
Control and Non-Payload Communications (CNPC) Link for UAS

Fix Satellite Station (FSS) Space Station

Ku/Ka band

UA Earth Station (UAES)

UAS CNPC Links
1+2: Forward link (Remote pilot to UA)
1: Forward uplink (E-s)
2: Forward downlink (s-E)
3+4: Return link (UA to remote pilot)
3: Return uplink (E-s)
4: Return downlink (s-E)

Line-of-Sight (LOS)
5GHz band (5030-5091MHz) was allocated worldwide (at the WRC-12)

Beyond-Line-of-Sight (BLOS)
5GHz band (5030-5091MHz) was allocated worldwide (at the WRC-12)
Allocations of Ku/Ka bands in the FSS band are being discussed now (toward the WRC-15)
Recognizing the increased need for the short-range usages of small UAVs or remote-control robots for several applications, Ministry of Internal Affairs and Communications (MIC) began to look into the feasibility of the frequency allocation for control and application links of small UAs with small transmission power in Japan.

A drone with radiation symbol was found on the roof of the prime minister’s office in May 2015.

- The ruling Liberal Democratic Party is drawing up a bill to designate no-fly zones over important national facilities, including the prime minister’s office, and impose penalties on violators.

- The government is considering banning drone flights at night, according to an outline of new regulations on how the unmanned aircraft should be used.

- The envisaged rules will only allow users who take certain safety steps to fly their drones in residential areas and near airports.

- Drone manufacturers will be required to develop a system that uses GPS to limit the flight of drones in such restricted areas.
Frequency Regulations on UAS

- The frequency band 5 030–5 091 MHz was allocated for the CNPC link at WRC-12
  - The definition of internationally standardized system is required under the footnote 5.443C of ITU-R Radio Regulations
  - NICT is interested in usage of the frequency band 5 030–5 091 MHz for CNPC link which realizes safe operations of small UAs in a short range with small transmission power.

- Several discussions on UAS frequency usages including channel plan are carried out in ICAO
  - ICAO has a policy that calls for enacting a general framework of flight rules by around 2018
  - The technological and industrial development of the field of unmanned aircraft in Japan has been stared

- UAS Traffic Management (UTM) system by NASA
DEVELOPMENT OF UAS WIRELESS RELAY NETWORK
In past disasters such as Great Hansin Earthquake and Great East Japan Earthquake, some isolated areas appeared in disasters area.

The transportation system and communication system were interrupted by earthquake and tsunami

The demand of wireless relay network using unmanned aircraft system has grown
NICT started R&D on disaster-resilient wireless communication system using small unmanned aircraft system (UAS) in order to ensure the communication infrastructure between the isolated and the non-isolated areas at the time of disasters.

**Advantages:** Rapid deployment, Low operation cost, No runways needed

- Hand-launch small UA-1 (On-board repeater)
- Hand-launch small UA-2 (On-board repeater)
- Air-to-air relay for communication between more distant GSs
- Safety confirmation, E-mail, and voice are available by Wi-Fi bridge via UAS
- Wi-Fi zone
- Wi-Fi access point
- GS-A: Small portable set
- Power generator
- GS-B: Hand-launch
- To Internet
- Isolated area
- Non-isolated area
- Terrestrial N/W damaged
PUMA-AE

<table>
<thead>
<tr>
<th>Name</th>
<th>PUMA-AE (AeroVironment, UAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wingspan, Weight</td>
<td>2.8m, 5.9kg</td>
</tr>
<tr>
<td>Payload</td>
<td>0.5kg</td>
</tr>
<tr>
<td>Flight time, range</td>
<td>2-4 hours, 15-20 km</td>
</tr>
<tr>
<td>Wind speed</td>
<td>25 knots (13m/s)</td>
</tr>
<tr>
<td>Max. flight ceiling</td>
<td>5000 m (200~400m in the demo)</td>
</tr>
<tr>
<td>Power, operation</td>
<td>Electric, hand launch, deep-stole landing, autonomous flight by GPS and other sensors, water proof</td>
</tr>
</tbody>
</table>

Puma AE (All Environment)

Onboard wireless relay station (OWRS)
<table>
<thead>
<tr>
<th>Model</th>
<th>Shrike (AeroVironment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wingspan Weight</td>
<td>0.91 m, 2.5 kg, Wireless communication, High resolution EO &amp; IR modular payloads</td>
</tr>
<tr>
<td>Payload weight</td>
<td>0.5～1.0 kg</td>
</tr>
<tr>
<td>Endurance, Range</td>
<td>0.6 hours, 5km</td>
</tr>
<tr>
<td>Speed</td>
<td>30 knots</td>
</tr>
<tr>
<td>Features</td>
<td>VTOL, Rechargeable battery, GCS: AV’s common ground control station</td>
</tr>
</tbody>
</table>

Shrike’s modular payload bays support multiple missions, including aerial reconnaissance, surveillance, route clearance, counter IED, mapping, hover-and-stare, perch-and-stare and payload delivery.

Remote landing, perch and stare up to 6 hours with full motion video

Laser reflector for satellite communication
Payload for relaying the data

<table>
<thead>
<tr>
<th>Pictures</th>
<th>Transceiver of on-board</th>
<th>Transceiver of GS</th>
<th>Antenna of GS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>2 GHz (Experimental)</td>
<td>8 MHz</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal power</td>
<td></td>
<td>2 W</td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td></td>
<td>MSK</td>
<td></td>
</tr>
<tr>
<td>MAC</td>
<td>TDMA/TDD, 33 msec/frame</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna for GS</td>
<td>planar patch antenna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna for On-board</td>
<td>λ/4 whip antenna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data rate/Throughput</td>
<td>6 Mbps/400 kbps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame synchronization</td>
<td>1PPS by GPS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

500g
Urban area vs. Rural area

- Transmission rate = 100Kbps
- UDP protocol

Transmission:
- GS-b: 90 kbps, 21km
- GS-a: 98 kbps, 12km
- Pacific Ocean

Location:
- Taiki-cho

Notes:
- (AGL=400m~700m)
Urban area vs. Rural area

- Transmission rate = 100Kbps

Sendai Station

(UA) UA 11.6km (AGL=300m)

(GS-a) 3.5km

(GS-b) 11.6km

Pacific Ocean

(UA) 97 kbps

(GS-a) 49 kbps

(GS-b) 33 kbps

(UA) 84 kbps
Demonstration Examples of Wireless Relay System using UAS

- Utilization in agriculture, tracking of wild animal, monitoring of environmental level, and disaster medical by using on-board video camera or on-board transponder.
- We have conducted on the demonstration and experimental measurement all over JAPAN.
- Total number of flights is over 130 times, total flight time is over 80 hours.

NICT has submitted an application form for permission of flight or a report form for flight with domestic aviation act accordingly to the place and flight altitude.

<table>
<thead>
<tr>
<th>Place</th>
<th>Date</th>
<th>UA type</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memuro, Hokkaido</td>
<td>June 2014</td>
<td>2GHz CNPC UA</td>
<td>Small UA utilization in Agriculture</td>
</tr>
<tr>
<td>Sakaide, Kagawa</td>
<td>May 2014, May 2015</td>
<td>2GHz CNPC UA, 5GHz CNPC UA</td>
<td>Small UA utilization of Disaster Medical Assistance Team (DMAT)</td>
</tr>
<tr>
<td>Shirahama, Wakayama</td>
<td>March 2014</td>
<td>2GHz CNPC UA</td>
<td>Demonstration experiment of collaboration of UA based wireless relay with the mobile operators network via femto cell</td>
</tr>
<tr>
<td>Tomioka, Fukushima</td>
<td>Oct 2014</td>
<td>2GHz CNPC UA</td>
<td>Tracking of wild boars in the restricted residence area by radioactive materials</td>
</tr>
<tr>
<td>Shimanto, Kochi</td>
<td>Feb. 2015</td>
<td>5GHz CNPC UA</td>
<td>Demonstration experiment of cooperation of UA based wireless relay with the mobile operators network via femto cell</td>
</tr>
<tr>
<td>Odawara airport, (Shizuoka)</td>
<td>Dec. 2013, Dec. 2014</td>
<td>2GHz CNPC UA</td>
<td>Interview of TV program &quot;WBS&quot; on TV TOKYO, etc.</td>
</tr>
<tr>
<td>Sakanayama village, Kanagawa</td>
<td>March 2013</td>
<td>2GHz CNPC UA</td>
<td>Flight training</td>
</tr>
</tbody>
</table>
Demonstration: Tracking wild boars
(2014.10 Fukushima : difficult-to-return zone)

Small UA
(Collection of log data, down load the log data)

Log data (GPS information, radiation levels)

150MHz帯

430MHz帯

Control & Command Link for UA

Measurement of radiation levels using wild boars activities

Wild boars move in area of the high radiation levels

Coverage area: 20km

Collar-type transceiver (GPS, 150MHz) On board receiver

Image of tracking
DEVELOPMENT OF ON-BOARD ANTENNA FOR UAS
World Situation of On-Board Internet Access

- Lufthansa
- Panasonic (USA)
- Singapore
- ATG (800 MHz)
- Aircell (USA)
- JAL
- Gogo
- Ku Band
- Ku Band
- L Band
- Ka Band
- Americas
- Row 44 (USA)
- Aeros-mobile (UK)
- GSM
- Inmarsat (UK)
- SwiftBroadband
- ViaSat (USA)
- ANA
- American
- Domestic
- International

L-, Ku-Band → Ka-Band
Commercial Aviation Market Forecast

The aviation market

World fleet to double in size over the next 20 years!!

=> More frequency resources are required

Working Party 4A Workshop on Earth Stations on Mobile Platforms (ESOMP), Geneva, Switzerland, 7 October 2013
Candidate Unmanned Aircrafts for the Research

Small type UAs

Medium and Large type UAs
Require Beyond-Line-of-Sight (BLOS) operations

Target UAs of this research
Design Objective of On-board Ka Band Antenna for UAS

- The angle range of the antenna tracking by considering the longitude and latitude from Japan to track the stationary satellites, and control of the antenna beam.
- The maximum communication speed is 5 Mbps
- Whenever possible, to reduce the size, weight, power saving
- Low height of the antenna mounting system
- Wide bandwidth to satisfy the ESOMPs of the Ka band (27.5 ~ 30.0GHz/17.3 ~ 20.2GHz band)
  - ESOMPs: Earth Stations on Mobile Platforms
- Off-axis e.i.r.p. satisfies ITU-R Recommendation S.524-9
- Misspointing of antenna beam toward satellite must be within 0.2 degrees.
Key Points of Tracking Antenna Design

Off-axis antenna gain

Mispointing error
Requirement for UAS Ka-band Communications

- **ITU-R S.2223**
  - Technical and operational requirements for GSO FSS earth stations on mobile platforms in bands form 17.3e to 30.0 GHz

- **ITU-R Report M.2171**
  - Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace

- **ITU-R Rec S.524-9 Mask**
  - “...earth stations operating in GSO networks in the FSS transmitting in the 27.5-30 GHz frequency band be designed in such a manner that at any angle, $\varphi$, which is $2^\circ$ or more off the main lobe axis of the earth station antenna, the e.i.r.p. density in any direction within $3^\circ$ of the GSO should not exceed the following values:

  **Angle off-axis Maximum E.I.R.P. per 40 kHz**

  - $2^\circ \leq \varphi \leq 7^\circ$ (19 – 25 log $\varphi$) dB(W/40 kHz)
  - $0 \leq \varphi \leq 9.2^\circ$ –2 dB(W/40 kHz)
  - $0 \leq \varphi \leq 48^\circ$ (22 – 25 log $\varphi$) dB(W/40 kHz)
  - $48^\circ \leq \varphi \leq 180^\circ$ –10 dB(W/40 kHz).”
FCC Rules and Conditions

- Peak mispointing 0.2 degrees or as declared by applicant
  - Must make detailed interference showing if not using 0.2 deg limit
- Must meet FCC off-axis power density limits or coordinate excess
- Tx inhibit within 100 ms if
  - Mispointing exceeds 0.5 deg or declared limit
  - EIRP density exceeds limits
  - Loss of receive signal
- Terminal subject to control by a NCMC (language per M.1643)
- Terminal must be self monitoring, Tx shutdown if fault occurs
- Data logging of vehicle location & attitude (i.e., lat/long/alt, and pitch/yaw/roll), Tx frequency, channel BW, and satellite used
  - Log every 20 minutes (ESV), 6 minutes (VMES) 1 minute (ESAA)
- Protect Terrestrial Facilities: Radio Astronomy, NASA TDRS, and FS
- Must comply with RF exposure labeling requirements

## Comparison of Specifications of Ku and Ka Band Antennas

<table>
<thead>
<tr>
<th>Type</th>
<th>HR6400 RF</th>
<th>—</th>
<th>—</th>
<th>MODEL 2340</th>
<th>Our antenna</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>AeroSat</td>
<td>EMS</td>
<td>QEST</td>
<td>Viasat</td>
<td>NICT</td>
<td>—</td>
</tr>
<tr>
<td>Picture</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>—</td>
</tr>
<tr>
<td>Equivalent aperture size</td>
<td>—</td>
<td>—</td>
<td>39cm (estimated)</td>
<td>39cm (estimated)</td>
<td>Φ37.5cm</td>
<td>—</td>
</tr>
<tr>
<td>Height</td>
<td>22cm</td>
<td>20cm</td>
<td>21cm (estimated)</td>
<td>21cm</td>
<td>26cm</td>
<td>△</td>
</tr>
<tr>
<td>Diameter rotation</td>
<td>82cm</td>
<td>94cm</td>
<td>82cm (estimated)</td>
<td>81cm</td>
<td>90cm</td>
<td>△</td>
</tr>
<tr>
<td>Weight</td>
<td>34kg</td>
<td>39kg</td>
<td>41kg (estimated)</td>
<td>34kg</td>
<td>24kg</td>
<td>◎</td>
</tr>
<tr>
<td>G/T</td>
<td>12.7dB/K</td>
<td>unknown</td>
<td>11.1-12.4 dB/K ?</td>
<td>11.3 dB/K</td>
<td>13.4dB/K@19.2GHz z</td>
<td>◎</td>
</tr>
<tr>
<td>EIRP</td>
<td>42.5dBW</td>
<td>unknown</td>
<td>44-46dBW ?</td>
<td>43.5dBW</td>
<td><a href="mailto:48.1dBW@29.0GHz">48.1dBW@29.0GHz</a> z</td>
<td>◎</td>
</tr>
<tr>
<td>Polarization</td>
<td>—</td>
<td>—</td>
<td>fix</td>
<td>switchable</td>
<td>fix</td>
<td>○</td>
</tr>
<tr>
<td>Freq. TX</td>
<td>14.0-14.5GHz</td>
<td>unknown</td>
<td>29.0-30.0GHz</td>
<td>28.1-30.0GHz</td>
<td>27.5-30.0GHz</td>
<td>◎</td>
</tr>
<tr>
<td>Freq. RX</td>
<td>10.7-12.7GHz</td>
<td>unknown</td>
<td>19.2-20.2GHz</td>
<td>18.3-20.2GHz</td>
<td>17.3-20.2GHz (ESOMPs)</td>
<td>◎</td>
</tr>
</tbody>
</table>
### Results of Antenna Design

<table>
<thead>
<tr>
<th>No</th>
<th>Items</th>
<th>Values</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>G/T</td>
<td>Over 10.0 dB/K@18.9G Hz</td>
<td>Information speed: 5Mbps Margin: 1.5dB</td>
</tr>
<tr>
<td>2</td>
<td>e.i.r.p.</td>
<td>Over 46.7 <a href="mailto:dBW@28.6G">dBW@28.6G</a> Hz</td>
<td>Information speed: 5Mbps Margin: 0.8dB</td>
</tr>
<tr>
<td>3</td>
<td>e.i.r.p. density</td>
<td>26.5 dBW/40kHz @28.6GHz</td>
<td>Information speed: 5Mbps Symbol rate: 6.02Msps</td>
</tr>
<tr>
<td>4</td>
<td>BUC output</td>
<td>10W</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No</th>
<th>Items</th>
<th>Values</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tx Frequency</td>
<td>27.5-30.0 GHz</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Rx Frequency</td>
<td>17.3-20.2 GHz</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Off-axis e.i.r.p.</td>
<td>ITU-R S.524-9 24.5dBW/40kHz</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Size</td>
<td>Height &lt; 22.2 cm</td>
<td>Without radome</td>
</tr>
<tr>
<td>5</td>
<td>Polarization</td>
<td>Tx: right-handed circularly</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>G/T</td>
<td>Over 10.0 dB/K@18.9GHz</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>e.i.r.p.</td>
<td>Over 46.8dBW</td>
<td></td>
</tr>
</tbody>
</table>

As the reference satellite, we assume a broadband communication satellite system ‘WINDS’ developed as an experimental communication broadband satellite.
Structure of Radiation Unit

Hybrid analysis of physical optics (PO) approximation and finite element method (FEM) was applied*  

Design Drawing of On-board Antenna

Antenna height: 26 cm

Total antenna weight: 24 kg
Appearance of Radiation and Drive Units of On-board Antenna

Horn antenna  cone

Antenna mount  Main reflector  Sub reflector
### Evaluation Results – Receiving G/T

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Unit</th>
<th>17.7 GHz</th>
<th>18.3 GHz</th>
<th>18.9 GHz</th>
<th>19.2 GHz</th>
<th>20.2 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>dBi</td>
<td>34.0</td>
<td>34.7</td>
<td>35.2</td>
<td>35.7</td>
<td>35.8</td>
</tr>
<tr>
<td>System Noise Temp</td>
<td>dB</td>
<td>22.5</td>
<td>22.5</td>
<td>23.0</td>
<td>22.3</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>174.8</td>
<td>176.7</td>
<td>197.5</td>
<td>167.3</td>
<td>179.0</td>
</tr>
<tr>
<td>Antenna noise temp</td>
<td>K</td>
<td>86.1</td>
<td>78.3</td>
<td>106.4</td>
<td>74.2</td>
<td>85.9</td>
</tr>
<tr>
<td>LNA noise temp</td>
<td>K</td>
<td>88.7</td>
<td>98.4</td>
<td>93.1</td>
<td>93.1</td>
<td>93.1</td>
</tr>
<tr>
<td>G/T</td>
<td>dB/K</td>
<td>11.5</td>
<td>12.2</td>
<td>12.2</td>
<td>13.4</td>
<td>13.2</td>
</tr>
</tbody>
</table>

We confirmed the developed radiation unit of the on-board antenna satisfied the receiving G/T, that is, over 10dB/K to realize 5 Mbps communication speed.
2-D Measurement by Near-field Measurement System
Example of transmitting antenna pattern

Frequency : 27.0GHz
Gain : 39.3 dBi

Far-field amplitude of Ka_ant_2700.NSI
Example of receiving antenna pattern

Frequency: 17.0 GHz
Gain: 33.3 dBi

Far-field amplitude of Ku_ant1701.NSI

Azimuth cut

Elevation cut
We confirmed the developed radiation unit of the on-board antenna satisfied the antenna requirements defined in ITU-R S.524-9.
Tracking System

- **AZ**: 360° (continue)
- **EL**: 0°～90°
## Evaluations of Tracking Accuracy

<table>
<thead>
<tr>
<th>Drive range</th>
<th>AZ: 360° (continual move)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EL: 0° ~ 90°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drive speed</th>
<th>AZ: &gt; 40° / sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EL: &gt; 25° / sec</td>
</tr>
</tbody>
</table>

Confirm the tracking error within 0.2 degrees including over-shoot.
Evaluations of the Antenna using Actual Airplane in 2015

- WINDS Satellite
- Experiment using airplane in Hawaii, USA
- Earth station of NICT In Japan
- BUC
- Tx RF
- CDM 570L
- Modem
- On-board tracking antenna for unmanned aircraft system
- UAS Earth station
- Rx IF
- Antenna Control Unit
- CDM 570L
Conclusions

- We developed a UAV-based wireless relay network system in natural disasters

- Current status of the developing of the on-board Ka band tracking antenna for unmanned aircraft system
  - Status of current standardization
  - We developed
    - a radiation unit of the on-board antenna and evaluated its characteristics
    - on-board tracking unit

- Future works
  - 2015 year
    - Experiments and evaluations of the antenna using actual airplane