AUTHOR(S): GONZALEZ, J.D.T. and FUNG, W.-K.

TITLE: A pilot study on aeronautical surveillance system for drone delivery using heterogeneous software defined radio framework.

YEAR: 2017

Publisher citation: GONZALEZ, J.D.T. and FUNG, W.-K. 2017. A pilot study on aeronautical surveillance system for drone delivery using heterogeneous software defined radio framework. In Proceedings of the IEEE international real-time computing and robotics conference (IEEE RCAR 2017), 14-18 July 2017, Okinawa, Japan. New York: IEEE [online], pages 499-504. Available from: https://doi.org/10.1109/RCAR.2017.8311912

OpenAIR citation: GONZALEZ, J.D.T. and FUNG, W.-K. 2017. A pilot study on aeronautical surveillance system for drone delivery using heterogeneous software defined radio framework. In Proceedings of the IEEE international real-time computing and robotics conference (IEEE RCAR 2017), 14-18 July 2017, Okinawa, Japan. New York: IEEE, pages 499-504. Held on OpenAIR [online]. Available from: https://openair.rgu.ac.uk

A Pilot Study on Aeronautical Surveillance System for Drone Delivery using Heterogeneous Software Defined Radio Framework

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***Abstract*—This paper presents a heterogeneous computing framework to interface single board computers (SBC) to (i) distinct type of computing nodes, (ii) distinct operating systems, and (iii) distinct software applications for aeronautical surveillance system for drone delivery. The implementation platform selected is the Beagle Bone Black (BBB) having the operating system (OS) Linux Ubuntu 14. The computing nodes the BBB interfaces to are: (i) a personal laptop (MacBook Pro), (ii) a virtual machine, and (iii) two servers with distinct OSs. The software applications the BBB interfaces to are: (i) Gqrx, (ii) GNURadio, (iii) Google Earth, (iv) systems took kit (STK), and (v) Matlab. This heterogeneous computing framework, with the potential for incorporating specialized processing and networking capabilities, allows scalability for system integration to existing surveillance system for manned aircrafts. The proposed system successfully decodes the location of aircraft in real-time.**

Keywords—Beagle Bone Black, heterogeneous computing, networking, single board computer, SBC, Software Defined Radio, SDR, STK, RTL-SDR.

I. INTRODUCTION

An aeronautical surveillance system "provides the aircraft position and other related information to the air route traffic control centre (ARTCC) and/or airborne users" [BaVC14]. Hence, surveillance is responsible for updating flight plans, improving estimates at future waypoints and also removing the workload for pilots reducing voice communication while they are in flight [BaVC14].

Accurate surveillance is the basis of future automated alerting systems. The ability to actively track aircraft enables air traffic controller (ATC) to have alerts when an aircraft deviates from its assigned altitude or route, or when the predicted future positions of two or more aircraft conflict. It also supports minimum safe altitude warnings, danger area warnings and other similar alerts [BaVC14].

Drone delivery is under testing in industry. Drone delivery seeks to safely deliver packages to customers and reduce emissions and costs. A couple of the hundreds of new industrial applications are: (i) Amazon Prime Air, which had a beta test delivery on 7 December 2016 with drones that autonomously take off, land, and return. The flight restrictions are an altitude less than 400 feet with a cargo of less than five pounds [Amaz17], and (ii) UPS drone-launching delivery truck [Alic17] aiming for making parcel service more efficient in rural locations. UPS did its beta test on 21 February 2017 showcasing a drone autonomously dropping off a package, and returning to the truck while the driver continued along a route. Drones would allow UPS to reduce emissions.

These beta tests have implications for the new form of services that drones would undertake in the short term. However, the main challenge is that the sky would become even busier and more congested when drone delivery becomes ubiquitous. This could potentially fuel the development of specialized monitoring systems focused on drones busy in the sky.

This paper shows experimentally that the drivers of a high-performance Digital Video Broadcasting-Terrestrial device (RTL-SDR) are capable of receiving radio signals with a very simple antenna and sending the sampled raw data to a single board computer ([Burc14] and [Keen14]), the Beagle Bone Black (BBB) for software defined radio (SDR) demodulation of FM radio and Automatic Dependent Surveillance Broadcast (ADS-B) signals. The RTL-SDR drivers allow: (i) accessing an unlimited frequency range by doing frequency hopping; (ii) capturing spectrum history; (iii) unlimited FFT binning; (iv) quantitative rendering as the exact power levels are recorded; and (v) alternative hardware setups.

The rest of the paper is organized as follows. Section II presents the design of the heterogeneous computing framework for software defined radio (SDR). Section III

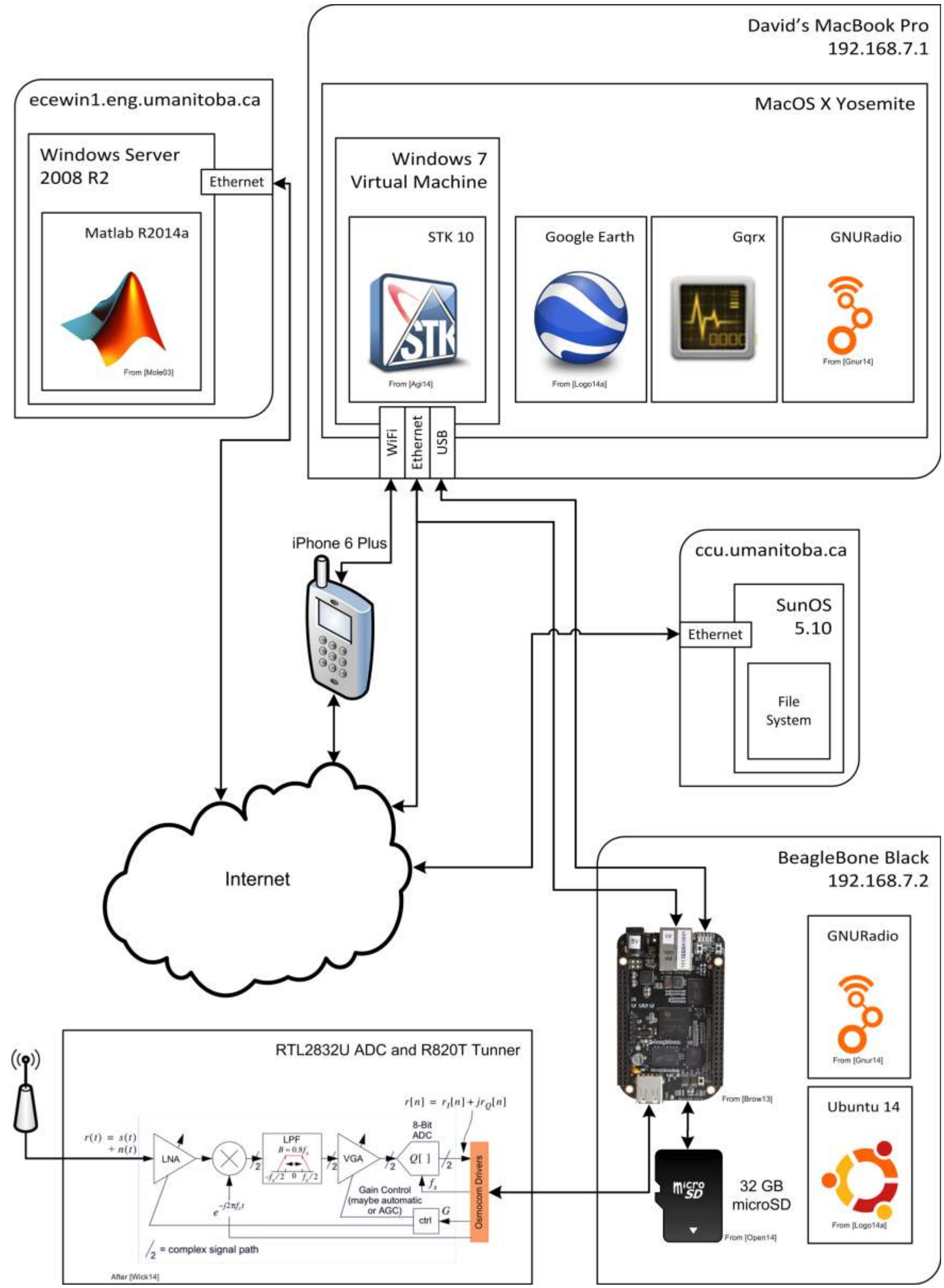

Fig. 1. Physical diagram communicating the BBB to (i) the MBP, (ii) the ecewin1.umanitoba.ca server, (iii) the ccu.umanitoba.ca server, and (iv) WiFi tethering through the iPhone 6 Plus.

demonstrates the basic functionalities of the tested SDR. Section IV describes the implementation of SDR based air traffic surveillance system for drone delivery and shows its basic operation. This paper is then concluded in Section V.

II. SOFTWARE DEFINED RADIO USING HETEROGENEOUS COMPUTING FRAMEWORK

The Beagle Bone Black is adopted as the main SDR platform. It has the following features: (i) a Sitara AM3358x, 1 GHz, ARM Cortex 8 microprocessor, (ii) a RAM memory of 512 MB DDR3 800 MHz, (iii) on-board flash storage of 4GB 8-bit eMMC, (iv) a 3D graphics accelerator SGX530 20 MPolygons/s, (v) a NEON floating point accelerator, (vi) a high speed USB 2.0 client port, (vii) a high speed USB 2.0 host port, (viii) a Universal Asynchronous Receiver Transmitter (UART) serial port, (ix) a microSD adapter, (x) a High-Definition Multimedia Interface (HDMI) adapter, (xi) stereo output, (xii) expansion connectors: a Multichannel Audio Serial Port (McAS), an Inter-Integrated (I^2C) port, 69 General Purpose Input/Output (GPIO) pins, 7 analog inputs, 4 timers, 4 serial ports, CAN bus and pulse width modulation capabilities, and (xiii) 2x PRU 32-bit microcontrollers [Beag14].

Flexibility and capacity of operation in heterogeneous computing environments are required features in modern embedded systems ([EkTM96], [ScFe14], and [ZhNC12]). This paper shows that it is possible to have such operational framework by using the BBB, which at the time of the running the experiments is one of the most complete and competitive single board computers (SBC) [Brow13]. The physical diagram shown in Fig. 1 provides the backbone for the different communication links between the computing nodes considered in the experiments run in this report. Figure 1 shows how the BBB interfaces physically to (i) a MacBook Pro (MBP) over virtual Ethernet over USB, (ii) one Windows 7 virtual machine residing in the MBP, (iii) two of the University of Manitoba servers (ecewin1.eng.umanitoba.ca and ccu.umanitoba.ca) via Internet, and (iv) a smartphone iPhone 6 Plus that provides alternative access to Internet through WiFi. The computing nodes shown in Fig. 1 have distinct OSs like iOS, MacOS, SunOS, Linux Ubuntu, and Windows Server 2008 R2. The software applications that the BBB interfaces with are: (i) Gqrx, (ii) GNURadio, (iii) Google Earth, (iv) systems took kit (STK), and (v) Matlab. This is a highly heterogeneous computing framework for the networking experiments for the BBB.

III. FUNCTIONALITY TESTS OF THE BEAGLE BONE BLACK HETEROGENEOUS NETWORK

In order to test the basic functionality of the proposed heterogeneous software defined radio framework, a working prototype is first constructed for FM radio demodulation. The prototype is then quickly reconfigured for ADS-B message demodulation and decoding, which is one of the fundamental functions of aeronautical surveillance systems.

A. Demodulating FM Radio

Computers have become powerful enough to perform mathematical calculations in software. This allowed the creation of advanced software defined radios (SDR) that previously required complicated hardware. A SDR receives an analog radio signal, which via an analog to digital converter (ADC) is digitized. The digitized signal is manipulated with digital signal processing software ([Carl14], [Kins14a], and [Kins14b]). Multiple open source SDR platforms exist. Two of them are utilized in this research with the BBB: GNURadio [Gnur14] allows quite sophisticated and custom implementations to fully unlock digital processing for SDR and Gqrx [Gqrx14] offers a GUI and supports many of the SDR hardware available.

1) Gqrx

Gqrx is a SDR receiver powered by the GNURadio and the Qt graphical toolkit. Gqrx supports many of the SDR hardware available. Gqrx is free and user/hacker friendly. It comes with source code licensed under the GNU General Public license allowing anyone to fix and modify it for whatever use. The latest stable version of Gqrx is available for Linux, FreeBSD and Mac and it offers many features [Gqrx14].

This experiment requires the following signal acquisition hardware: a small simple antenna connects via a MCX adapter to a RTL2832U (RTL-SDR) that is a high-performance Digital Video Broadcasting-Terrestrial (DVB-T) and Coded Orthogonal Frequency Division Multiplexing (COFDM) demodulator that supports a USB 2.0 interface according to Realtek [Real14]. Although no datasheets are available for the RTL-SDR from the vendor unless you sign a non-disclosure agreement, as of now it is public knowledge that the RTL-SDR has two 8-bit ADCs for inphase/quadrature (I/Q) sampling. This is related to the Wessel (complex) plane or to the negative/positive parts (offsets) from the carrier (DC). In practice an ADC works up to a certain frequency. The RTL-SDR ADCs work past 20 MHz. For digitizing higher frequency signals, a mixer stage is required to convert the received frequencies down to frequencies the ADCs can handle. This is the function of the tuner chip (*e.g.*, R820T or E4000) [Carl14].

The RTL-SDR was originally used in DVB-T in Europe. However, in 2012 hackers (hardware hacker Eric Fry, Linux driver developer Antti Palosaari, and the Osmocom team [Carl14]) found the way of how to use the RTL-SDR chip in SDR [Cass13]. The R820T tuner allows the RTL-SDR to pick radio frequencies from 24 all the way to 1,700 MHz. Other technical specifications of the RTL-SDR are: a maximum bandwidth of 3.2 MHz (approximately 2.8 MHz is the stable upper limit when sending the data samples through USB 2.0), an embedded low noise amplifier (LNA) with a 4.5 dB noise figure [Carl14].

In this experiment a FM signal is received by the RTL-SDR. The data is then sent via USB to the BBB. The RTL-SDR is connected to the BBB via USB. The BBB sends the raw data further to the MBP running Gqrx, which demodulates the received FM signal into audio as shown in Fig. 2.

2) GNURadio

GNU Radio is a free software development toolkit that provides the signal processing runtime and processing blocks to implement software radios using readily-available, low-cost external RF hardware and commodity processors. It is widely used to implement real-world radio systems. GNURadio

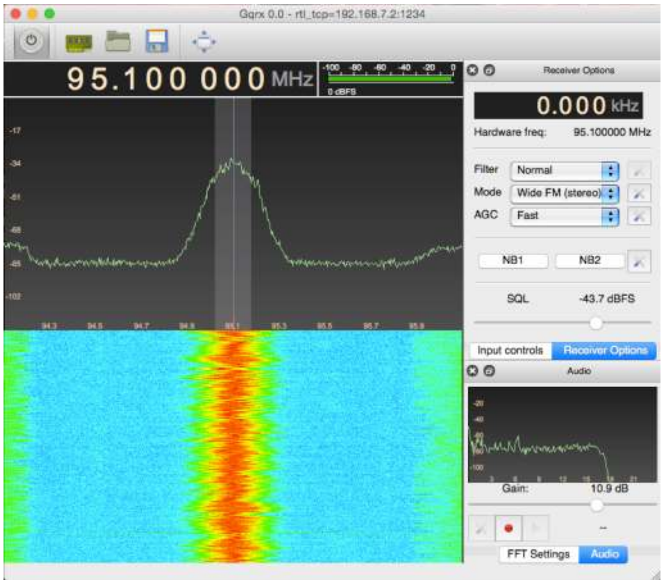

Fig. 2. Gqrx is running in the MacBook Pro (IP 192.168.7.1) and is manipulating the RTL-SDR connected to the BBB (IP 192.168.7.2) via the TCP port 1939. The CHVN 95.1 radio station is shown as well as the waterfall that depicts the carrier frequency behaviour.

applications are primarily written using the Python programming language, while the supplied, performance-critical signal processing path is implemented in C++ using processor floating point extensions where available. Thus, the developer is able to implement real-time, high-throughput radio systems in a simple to use, rapid application development environment [Gnur14].

This experiment uses GNURadio to get to analogous mechanisms that Gqrx utilizes under the hood to decode received radio signals. This experiment requires communication between the BBB and the MBP. Documents known as "flowgraphs" are developed in GNURadio companion that is an integrated development environment (IDE) for programming software-defined radios transmitters and receivers. The corresponding SDR flowgraph for a FM decoder was developed. It consists of the following modules: (i) *source driver* set to a sampling rate of 950 kHz, the tuner is set to 106.1 MHz and manual gain control (gain control can also be set to automatic (AGC)); (ii) a *rational resampler* that interpolates by 480 kS/s and decimates by 950 kS/s. This module leaves the signal in a smother shape and with a bandwidth of 480 kHz; (iii) a *wide band frequency modulator* (WBFM) receiver that extracts the audio from the frequency modulated signal. This module also decimates the signal 30 times to leave it in a bandwidth of 16 kHz; (iv) a *TCP sink* module defined as a client sends the data through Ethernet to the MBP (IP 192.168.7.1). Then, the date is processed and sent to the speakers for listen to the audio signal. The complementary flowgraph in GNURadio companion for listening to the FM radio was developed in the MBP. It consists of these modules: (i) a *TCP source* module defines as a server for receiving the data from the BBB (IP 192.168.7.2); (ii) a *multiply constant* that allows controlling the volume; and finally (iii) an *audio sink* that drives the MBP speakers with the received audio.

It is possible to listen to all the FM radio stations available in a given place by following either of both described procedures. These procedures were tested with local FM stations in Winnipeg, MB, Canada.

B. Demodulating ADS-B Signals

An ADS-B message, 112 bits long, is transmitted *unencrypted* from aircraft over a 1090 MHz data link each second to neigbouring aircraft or ground stations. An ADS-B message has the following five sections: (i) the first five bits indicate the type of message (downlink format), (ii) the next three bits specify the transponder capabilities, (iii) the following 24 bits denote the aircraft address, which is unique to an aircraft (similar to a MAC address in a computing system), (iv) the subsequent 56 bits conform the data field that provides the aircraft identity, position, and velocity, and (v) finally the remaining 24 bits are an error check sum for detection and correction of transmission errors [ACOS14]. ADS-B ground stations within range receive the broadcasted messages and relay the information via a networked backbone to ATC and properly equipped aircraft [McBM11]. Also, anyone with the proper skills and equipment can receive ADS-B messages, potentially tamper and inject them in this new surveillance system.

Since ADS-B messages are transmitted unencrypted over the 1,090 MHz frequency band, the BBB in conjunction with GNURadio utilities could demodulate and decode ADS-B messages content. The experiment setup is as follows: (i) The BBB runs the GNURadio utitilities. The utilities are configured having the driver set for the RTL-SDR as a source, 49 dB of gain, 2 MS/s, and key hole markup (KML) file capture active; (ii) The KML file, 2014_12_7_modes_rx_data.kml, is captured locally in the BBB. (iii) Software applications like Google Earth and STK running in the MBP natively and in a Windows 7 virtual machine respectively are capable of displaying airplanes data.

With the previously described setup, messages from an airplane flying over Winnipeg where decoded. Figures 3 and 4 show the location for flight CKK228 that belongs to China Cargo Airlines. This flight data are: coordinates -96.976615, 49.779798 and altitude 10,363 m/34,000 ft. My neighbour hood area, Branson Crescent, is also depicted in Fig. 3.

IV. Discussion

Radio demodulation via GNURadio played a central role in this research. Different GNURadio front ends are used (Gqrx and GNURadio-Companion) for digitally processing the demodulation when receiving a given signal. The FM demodulation shows audible clicks when listening to it. This phenomenon is because processing power of the BBB is overwhelmed at times. As of now, the hardware capabilities consider receiving signals only.

Aeronautical objects are part of our critical infrastructure and hostile entities wanting to disrupt or harm this network could cause that ghost airplanes could appear in graphical systems that ATC personnel could use. This aspect is not fully

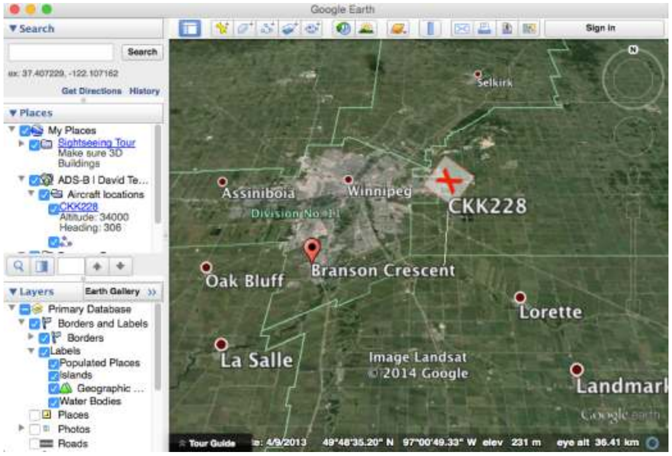

Fig. 3. Google Earth displaying location of flight CKK228. Coordinates: -96.976615, 49.779798. Altitude: 10,363 m/34,000 ft.

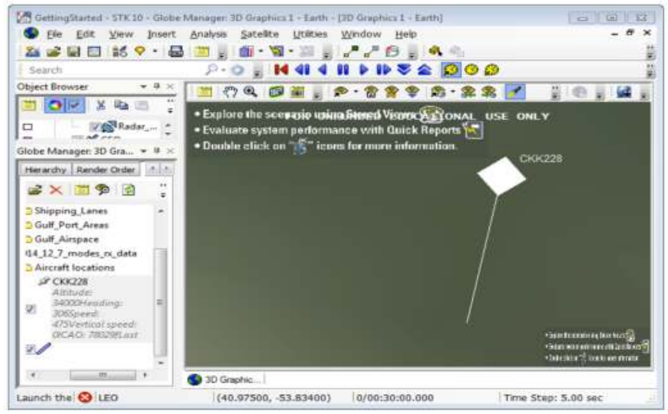

Fig. 4. STK 10 displaying location of flight CKK228.

presented in this report, but it is a security threat that is currently open in the ADS-B system.

Alternative interfacing applications between the BBB to digital to analog converters (DACs) like the DAC8562 and direct BBB pin manipulations from a Matlab instance running in the remote server ecewin1.eng.umanitoba.ca were considered and are indeed feasible. The logical link level that allows Matlab access the BBB environment has been achieved. Nevertheless, it must be stressed that remote and direct manipulation of SBC has paved the road of the Internet of Things (IoT), networked mechatronic and robotic systems. The cost and complexity to build and deploy systems like that incorporate a SBC has diminished substantially. Complex SDR systems requiring more powerful computers and alternative/support SDR based on SBC could be set as ground stations and access them remotely, possibly even through mobile apps linked to the IoT.

Through this research, a number of things show remarkable significance in engineering and digital communications: (i) SBC capabilities, (ii) SDR very advancing ecosystem and its applications, (iii) physically and logically linking computing nodes, and (iv) how some experiments could become non-repeatable in cyberspace, by the mere absence of a node, and how this affects tracking hostile attacks against a system.

ADS-B is one of the surveillance technologies available and suitable for providing ATC services for tracking aircrafts more accurately over conventional radar (20 m of precision compared with 300 m at 60 nautical miles where accuracy does not deteriorate as the range from the radar receiver increases [McBM11]). The Federal Aviation Administration (FAA), a United States Federal Government office whose primary mission is to “provide the safest, most efficient aerospace system in the world”, proposed a framework known as Next Generation (NextGen) in North America. It will replace eventually the current radar systems. Its major component is ADS-B that includes transmitting/receiving elements, ADS-B IN (allows the aircraft to receive data from ground stations and other aircrafts) and ADS-B OUT (allows the aircraft to transmit data to ground stations and other aircrafts) [ACOS14]. ADS-B also provides greater coverage, since ADS-B ground stations are much easier to deploy than radar systems. According to the FAA, there would be 800 ADS-B stations, placed 240 to 320 km apart, in the United States alone by 2020 [McBM11]. Hence, remote areas without radar coverage are becoming covered by ADS-B instead [BaVC14]. Aircraft with ADS-B systems onboard monitor all flight phases: push back, taxi and departure; climb and cruise; descent and approach; and landing, taxi and arrival [McBM11].

ADS-B can be considered one of the most important underlying technologies to transform air traffic control from the current grounded-based system to a satellite-based system by conferring precision and reliability for surveillance [BaVC14]. ADS-B relies on the global positioning system (GPS) for determining the aircraft location. The aircraft location is sent to the ATC and the pilot. Advantages of ADS-B include: (i) surveillance coverage in areas without primary and secondary radar (*e.g.*, operations with helicopters in oil platforms in the Gulf of México or in the Campos Basin in Brazil [BaHY12]), (ii) real-time broadcast of data, (iii) increase the ATC and pilot situational awareness, and (iv) allow the ARTCC to decrease securely the aircraft separation distance [ACOS14].

Even though ADS-B technology was developed primarily for improving situational awareness for manned aircrafts, it has appeared as either potential solution or requirement for sense and avoid systems (S&ASs) in unmanned aerial systems (UAS) [BaVC14].

V. Conclusions

The versatility of SBC has been shown via utilizing the BBB. Some capabilities of SDR have been explored by implementing demodulation of FM and ADS-B signals. These ideas are building blocks that could be extrapolated to more complex and higher computing performance equipment if required.

A working and complex heterogeneous environment has been shown. It allowed the integration of two servers of the University of Manitoba, a MBP (that also hosted a Windows 7 virtual machine), and a SBC (BBB). All the critical software runs in the BBB and the collected data is distributed to secondary nodes, the consumers, which had client applications like Gqrx, GNURadio-companion modules, Google Earth, STK, and Matlab. The integration of such framework has demonstrated that SBC are capable of relaying data across complex networks. This form of interfacing considering distinct computing nodes, distinct operating systems, and distinct software applications that relate to a SBC is relevant and provides insight about how flexible such devices are in SDR. Furthermore, the potential applications of drones in the short term pose challenges for new navigation and air surveillance systems and it would certainly contribute to the number of devices in the IoT.

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