LTE-BASED AERONAUTICAL MOBILE TELEMETRY – LAB AND FIELD TEST EXPERIMENTS

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ABSTRACT

Aeronautical mobile telemetry (AMT) based on 3GPP's LTE standard is implemented in a proof-of-concept system. The solution tackles the very high Doppler shifts expected in flight tests using an appliqué that can be inserted between the transmit/receive ports of the Test Article (TA) and the antennas. This appliqué estimates the Doppler shift and proactively compensates for it on the uplink signal being transmitted by the TA.

The overall system has been tested under different operational conditions in a laboratory setup as well as in the field. In the laboratory setup, the desired operating conditions are created with a set of Software-Defined-Radio-based channel emulators coupled with a computer to control their behavior. In order to carry out field tests, an operational LTE network has been created at Edwards Air Force Base (EAFB) with two base stations, backhaul links, and a core network.

In this paper, we provide descriptions of both laboratory and field test setups as well as the results of several tests that have been carried out to date. The results of lab and field tests lend strong support to the viability of this AMT solution.

1. INTRODUCTION

A successful implementation of Aeronautical Mobile Telemetry (AMT) within a 3GPP 4G-LTE-based wireless communication infrastructure requires certain challenges to be overcome. One such challenge is the high Doppler shift that is prevalent in typical AMT scenarios. Commercial LTE equipment, especially the base station receivers, is typically designed to handle Doppler shifts of the order of a few hundred Hz. (LTE base stations are also referred to as eNodeBs or eNBs.) In contrast, in AMT use cases, Doppler shifts can easily reach several kHz at higher carrier frequencies, particularly when the velocity of the Test Article (TA) aligns with the radio path. In such circumstances, the eNB receivers cannot decode the uplink signals they receive over the air interface unless the frequency deviation from the nominal center frequency is somehow brought within a few hundred Hz.

Our solution to the problem of high Doppler shifts includes a Doppler Estimation and Compensation (DEC) appliqué (see [1], [2]) that is inserted between the antennas and the corresponding transmit/receive ports of the LTE terminal located at the TA. The appliqué estimates the Doppler shift by processing uplink (UL) signals transmitted by the LTE terminal and proactively compensates for it on the signals it passes to the antennas from where they are transmitted towards the eNB. As a result, when these signals arrive at the eNB receiver, their center frequency is close to the UL frequency reference where the eNB expects to receive them. The appliqué has its own stable and accurate frequency reference, and has been designed to work with COTS LTE terminals. This arrangement ensures that the COTS LTE terminal located at the TA end of the link needs practically no alteration.

The rest of this paper is organized as follows: In Section 2, we present the problem of high Doppler shifts in AMT, and describe our appliqué-based solution to this problem. In Section 3, we describe the laboratory and field test setups that were implemented to test the appliqué-based solution in different operating conditions. Some of the results of the tests and their analysis are presented in Section 4, followed by a summary of our conclusions.

2. THE DOPPLER PROBLEM IN AMT AND THE BASICS OF DEC

Figure 1 schematically depicts the Doppler problem in AMT.

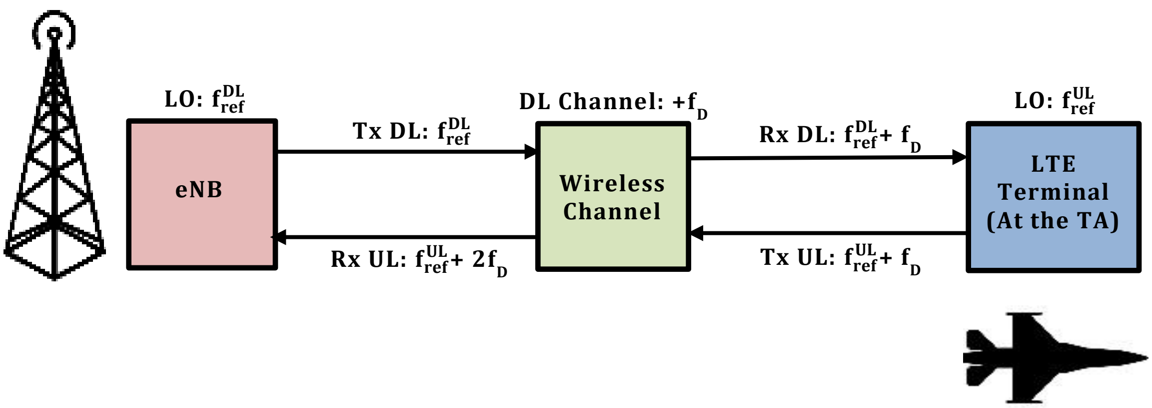

Figure 1: Schematic of the Doppler Problem with a Commercial LTE Device

As shown in Figure 1, the base station (eNB) transmitter transmits the downlink (LTE DL) signal at the corresponding reference (carrier) frequency, denoted by f_{ref}^{DL}. The wireless channel adds a Doppler shift (f_D) to this reference frequency so that when the LTE DL signals arrive at the TA transceiver, the carrier frequency appears to be $f_{ref}^{DL} + f_D$. The TA receiver derives its frequency reference from this perceived carrier frequency so that when it transmits uplink (LTE UL) signals towards the base station, the uplink carrier frequency gets shifted from the correct LTE UL reference frequency (f_{ref}^{UL}) by an amount equal to f_D. Thus, the carrier frequency associated with the LTE UL signals transmitted by the TA transceiver equals $f_{ref}^{UL} + f_D$. (While this description is applicable to a Time Division Duplex (TDD) LTE system, extensions to Frequency Division Duplex (FDD) are straightforward.) Over the path to the base station receiver, the wireless channel adds another Doppler shift (equal to f_D Hz) to these signals, so that when they arrive at the base station receiver, the effective LTE UL carrier frequency (from the viewpoint of the base station) is $f_{ref}^{UL} + 2f_D$. In other words, the LTE UL signals received by the base station are away from the expected carrier frequency by twice the Doppler shift associated with the wireless channel.

Inability to deal with a high Doppler shift is essentially an eNB problem. We have observed that commercial LTE terminals are able to track Doppler shifts of several kHz in the downlink (DL) signals and set their (derived) center frequencies in accordance with those shifts. However, eNB receivers typically fail to decode the UL signals received over the air interface if they deviate from the corresponding reference frequency (f_{ref}^{UL}) by more than a few hundred Hz. Our appliqué-based solution leverages the LTE terminals' ability to track large deviations in the DL center frequency to estimate the Doppler shift, and then compensates for it on the outgoing UL signals so that they arrive at the eNB with near-zero deviation from the correct frequency reference.

A schematic illustrating how the appliqué-based Doppler estimation and compensation scheme mitigates the Doppler problem is shown in Figure 2.

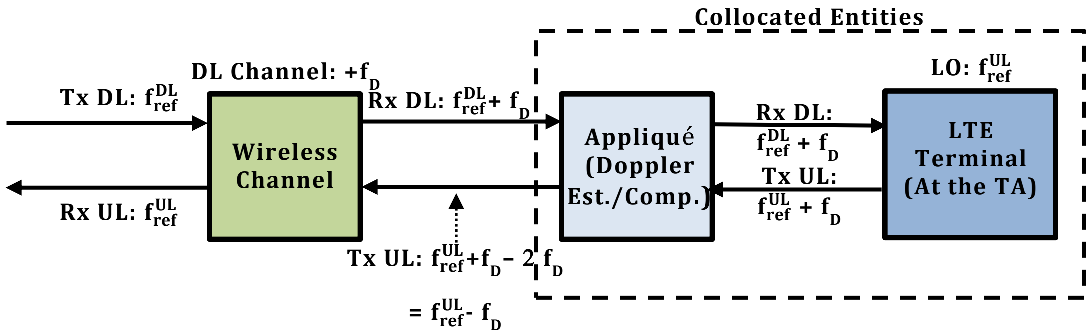

Figure 2: A Schematic Illustrating How the Appliqué Works

As shown in Figure 2, the DEC appliqué is placed between the LTE terminal's antenna unit and transmit-receive ports. It works as follows: The appliqué passes the DL signals received from the eNB essentially unchanged to the LTE terminal's receiver. The receiver derives its frequency reference from the received DL signal so that the Doppler shift of f_D in the DL signal is also reflected in the UL signals transmitted by the TA's LTE transmitter. Thus, the carrier frequency of these UL signals is $f_{ref}^{UL} + f_D$. The appliqué has a stable and accurate local oscillator that provides an accurate frequency reference. It samples the UL signals transmitted by the TA transmitter and processes them to estimate the amount by which these signals have deviated from the correct reference, i.e. from f_{ref}^{UL}. That is, the appliqué estimates the Doppler shift f_D, and applies a frequency compensation of $-2f_D$ to the UL signals before transmitting them towards the desired eNB. Thus, the signals transmitted by the terminal's antenna have their center frequency at $f_{ref}^{UL} - f_D$. Since the wireless channel adds a Doppler shift of f_D, when the UL signals arrive at the desired eNB, their carrier frequency is close to f_{ref}^{UL}, the correct UL carrier frequency.

3. DESCRIPTION OF LABORATORY AND FIELD TEST SETUPS

In order to determine how effectively the LTE Terminal-Appliqué combination can deal with the Doppler problem likely to be encountered in AMT, an elaborate laboratory test setup has been established. The idea is to emulate channel conditions such as the path loss and Doppler shift between base stations and the LTE terminal as functions of time that depend on the flight path associated with the TA. By including more than one base station (eNBs) in this setup, the ability of the LTE Terminal-Appliqué combination to deal with critical events such as handovers can also be tested. Figure 3, shown below, depicts a schematic of the lab test setup.

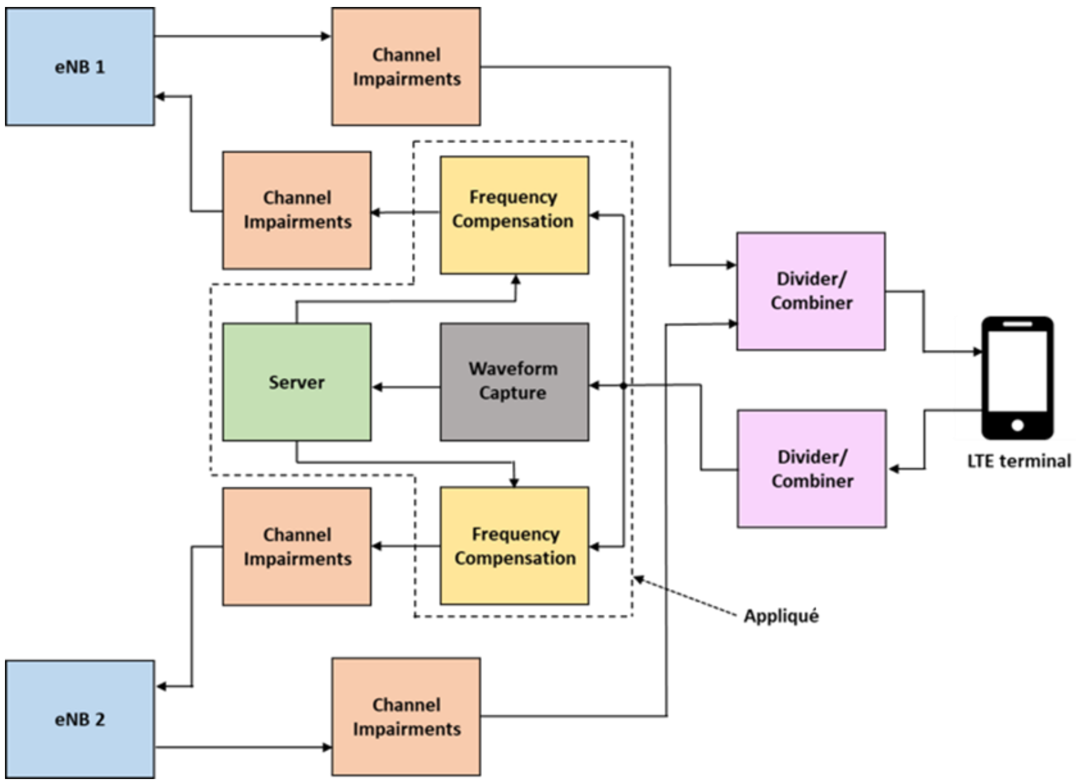

Figure 3: An Illustration of the Lab Test Setup

As shown in Figure 3, the lab setup comprises two eNBs and an LTE terminal. The two eNBs enable testing of handover events in the presence of the Doppler effect. The channels between the eNBs and the LTE terminal are emulated using Software-Defined Radios (SDRs). These SDRs are controlled with scripts to create several effects such as time-varying path-loss, Doppler shifts and delays. For example, using base station locations and a specified flight path for the test article as inputs, a computer (not shown in the figure) mathematically determines the path loss and Doppler shifts the test article experiences at different points in time. These values are fed to SDRs emulating channel impairments so that the DL and UL signals they output are appropriately modified to reflect the current path loss and Doppler shift when they reach the TA/eNB receivers. The appliqué itself is implemented using SDRs and a computer (labelled as "server" in Figure 3). In this implementation, the SDRs are responsible for waveform capture and frequency compensation while the computer carries out the more complex computations.

Figures 4 (a), (b), and (c) show an example of how the lab test setup emulates channel conditions corresponding to a test article's movement along a flight path. In this example, the flight path is assumed to be along the straight-line A→B, and the base station locations and orientations are as shown in Figure 5. The speed of the TA is 200 Knots and the altitude is 5,000 feet. Using these parameters, the TA's location is computed as a function of time, and, at each location, the path loss with respect to each of the two base stations is determined by calculating the corresponding distance. Finally, the Doppler shift with respect to each base station is determined by computing the component of the TA's velocity along the line connecting the base station to the TA's current location. The Doppler and path loss computations are fed to the appropriate SDR to modulate the corresponding signal.

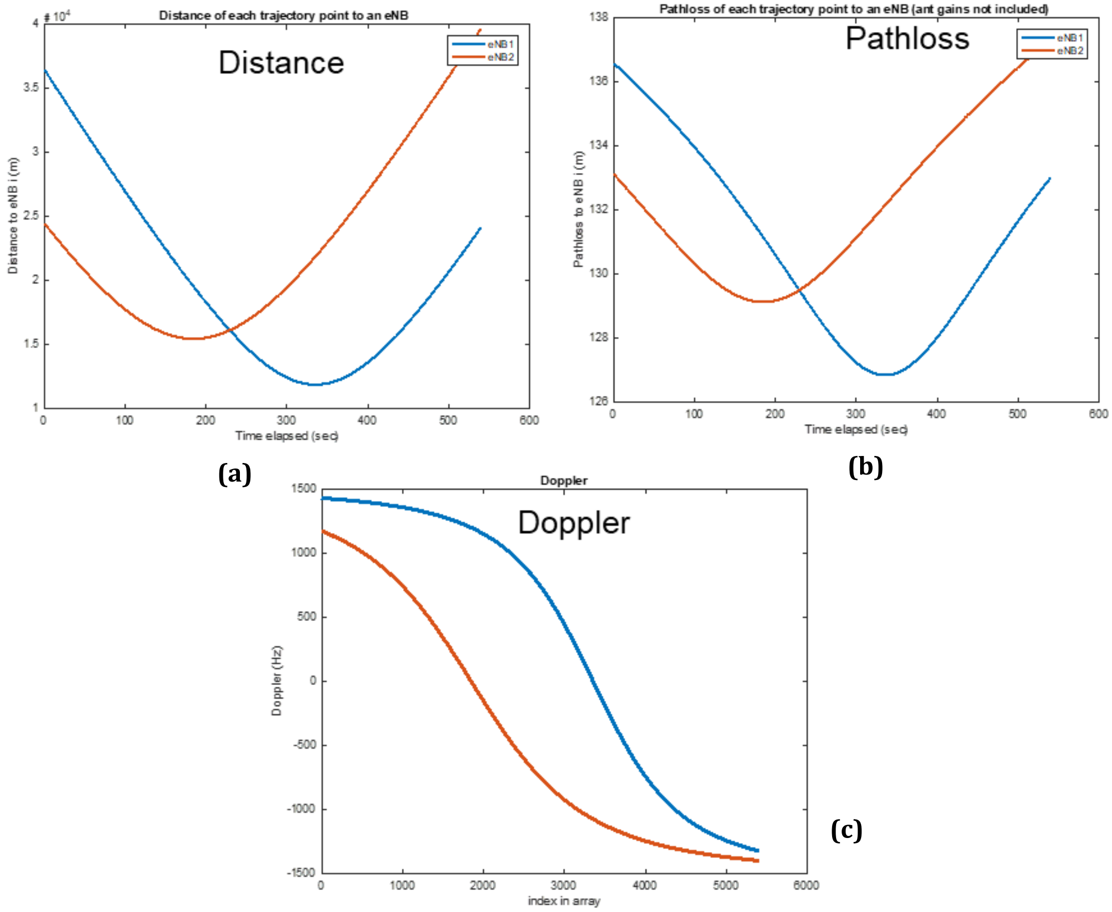

Figure 4(a), (b), (c): An Illustration of the Computation of Channel Conditions

Confirmation of the findings of laboratory experiments must be provided via over-the-air communications occurring at actual flying speeds, under real-life conditions. Consequently, a series of field tests have been planned. The field tests include ground tests as well as airborne flight tests. In this paper, preliminary ground-based field test results are presented.

For the field tests, an LTE network has been set up at Edwards Air Force Base (EAFB), with two base stations (eNBs), backhaul links, and an Evolved Packet Core (EPC). The EPC represents the LTE core network and comprises key elements such as the Mobility Management Entity (MME), the Serving Gateway (SGW) and the Packet Data Network (PDN) Gateway (PGW). In the LTE network deployed at EAFB, the EPC is implemented on a single server. The LTE network parameters and key performance indicators are visible to and managed through a Network Management System (NMS). An additional functional block called Integrated Cellular Network Controller (ICNC) is used for supervision and exercising network event controls such as handovers. Each eNB is equipped with a broad-beam antenna with 70-degree beam-width.

In the ground tests, The LTE terminal-appliqué combination was mounted in a car that was driven along roads within the coverage areas of the eNBs. The terminal maintained an LTE link with the two-eNB LTE network throughout the test. A GPS device was also placed in the car to determine its exact location as it was driven around. The location measurements provided by the GPS device were processed to obtain the actual Doppler shift between the LTE device and each eNB as a function of time. Figure 5 shows a schematic of the LTE network implemented for the field tests.

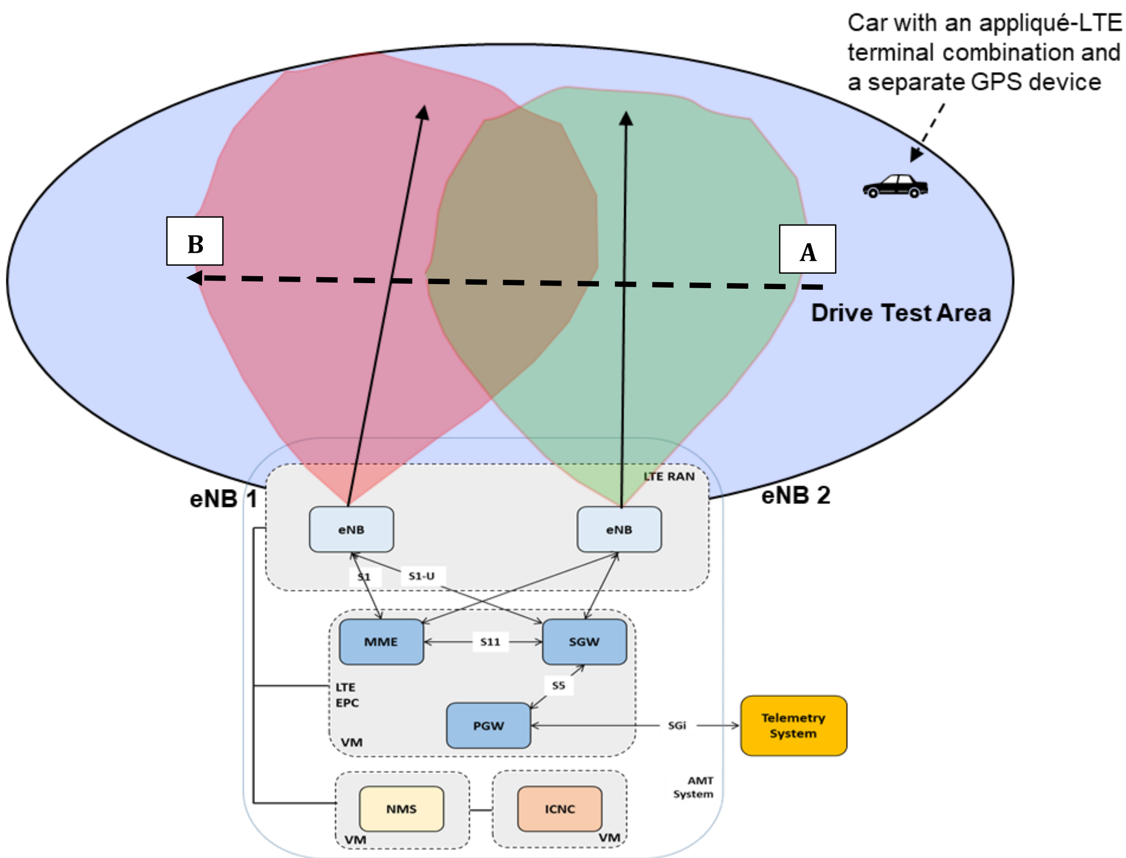

Figure 5: A Schematic of the LTE Network Used in Field Tests

4. TEST RESULTS

4.A Laboratory testing

We first describe results of some of the lab tests that were conducted to test the ability of the LTE terminal-appliqué combination to estimate and compensate for Doppler shift as it varies over a wide range of values. Figures 6a and 6b show results of two of the tests performed using the laboratory setup described earlier. In the first test (D1), the Doppler shift between the LTE terminal and its serving eNB was varied linearly between 0 and 3.0 kHz over a minute. The rate of change of the Doppler shift was steady at 50 Hz/sec. In the second test (D2), the Doppler shift was varied in a sinusoidal manner between -3.0 kHz and +3.0 kHz with a period of 60 seconds. (The peak rate of change of the Doppler shift was 300 Hz/sec near the zero crossing.)

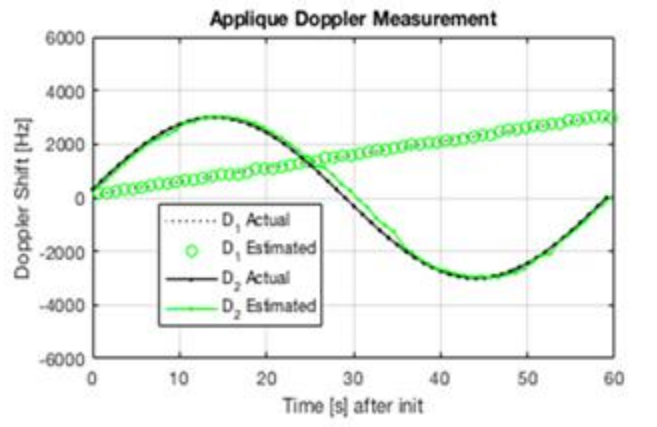

Figure 6a: Actual and Estimated Doppler Shifts in Lab Tests

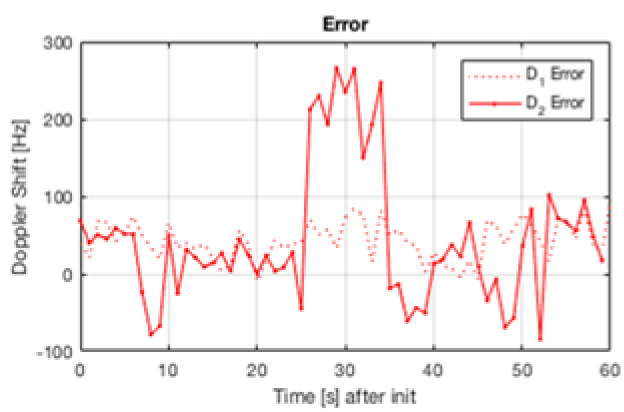

Figure 6b: Error Curves in Lab Tests

Figure 6a shows the actual Doppler shift and its estimate produced by the appliqué for both tests. Figure 6b shows the corresponding error curves. It is clear from the two figures that the appliqué is able to produce an accurate estimate of the Doppler shift in both tests. In the test where the Doppler varies linearly at 50 Hz/sec, the error is within 75 Hz. In the sinusoidal test, the error is normally within 100 Hz; however, near the zero-crossing where the Doppler shift rate of change is 300 Hz/sec, the error rises to about 300 Hz. Even this relatively large error is well within the range of the eNB receiver's tracking ability. Note that the link between the LTE terminal and its serving base station was maintained throughout the tests. Even when the Doppler shift was as high as 3.0 kHz, the appliqué had no difficulty estimating and compensating for the Doppler. In contrast, an LTE terminal with no help from the appliqué to compensate for the Doppler loses connectivity as soon as the Doppler shift exceeds a few hundred Hz.

We now describe an example of flight emulation tests. In this example, the lab setup shown in Figure 3 was used to emulate time varying channel conditions that a TA would experience on a flight from Point A to Point B as shown in Figure 5. The speed of the TA was set to 200 Knots and the altitude was 5000 feet. During flight emulation, the ICNC collected all measurements, events and other low layer data available from the eNBs. Two key readings from the system are shown in the plots displayed in Figure 7: a) Distance from the TA to the eNB it is connected to, and b) the Doppler estimate for the link between the connected (or attempting to connect) eNB and the TA. The former reading is obtained from the reported Timing Advance, which is logged by the eNB, while the latter is calculated by the appliqué and reported over the LTE link via an air-to-ground data connection to the ICNC. (This is a custom implementation).

In Figure 7, data points represent eNB2 (blue, positioned East) or eNB3 (red, positioned west). In the plots, it is evident that the TA initially connects to eNB2 and detects a neighbor (eNB3) during its flight. (The segment marked "Start" corresponds to the time before the test started when the TA was connected to neither eNB.) At some point in the trajectory, when the eNB3 signal is stronger than that associated with eNB2 by a sufficient amount, a handover occurs and the Doppler points jump to new values that reflect the corresponding measurements associated with eNB3.

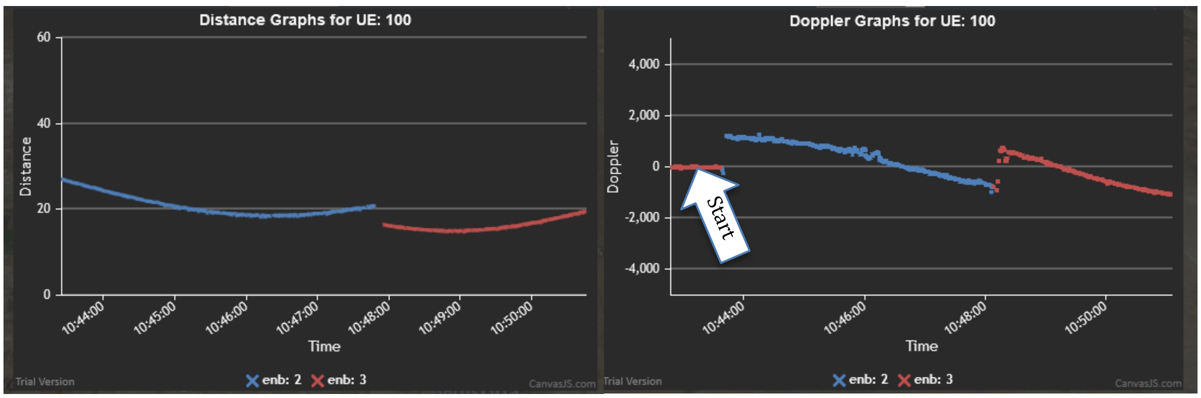

Figure 7: Real-time plots of Distance and Doppler of the TA at ICNC

We conclude this section on lab tests by presenting an example of protocol analysis testing. During flight emulation tests, the underlying LTE mechanisms were also analyzed to verify predictable behavior by both the TA and the eNBs. An area of interest is the time around handover occurrence, particularly between base stations experiencing different Doppler shifts. In the lab, artificial test conditions were generated in the flight emulation, to analyze handovers from eNB1 (at –D1 KHz of Doppler) to eNB2 (at +D2 KHz of Doppler).

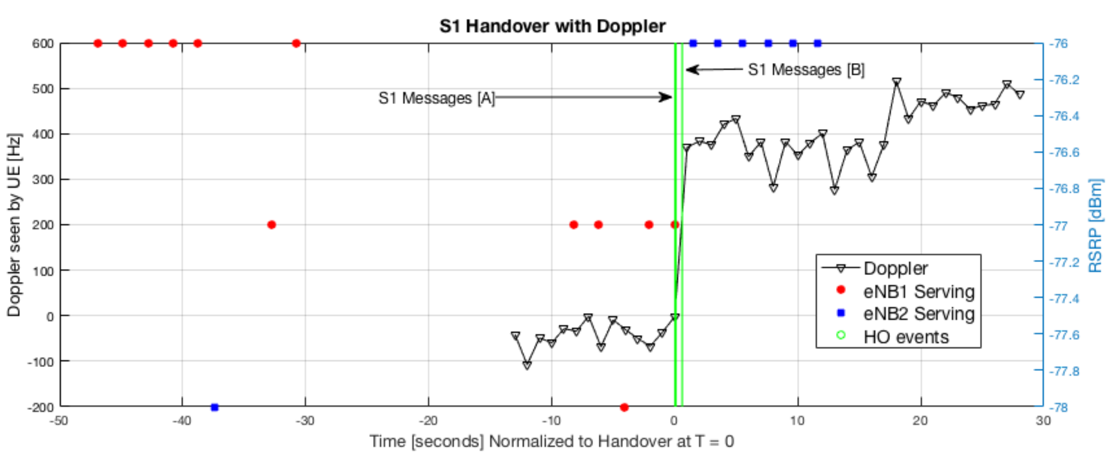

Figure 8: Key Link Parameters during a Handover

An example of the time series analysis during a handover is shown in Figure 8 for a -50 Hz to 550 Hz jump. The figure also shows the RSRP and Doppler estimates (the latter computed by the appliqué) for the serving eNB. In addition, the test involves analysis of the RRC messages exchanged during the handover. This example shown in Figure 8 represents a properly executed S1 handover per LTE specifications.

4.B Ground Field Tests

As mentioned in the previous section, the field tests involved an LTE terminal-appliqué combination mounted in a car driven on roads within the coverage area of the LTE network shown in Figure 5. The LTE terminal attempted to remain connected to the network throughout the tests. In cases where signals from the neighbor base station became stronger than the terminal's serving base station, the terminal was handed over to the neighbor. The key performance metrics of interest in these tests were: a) the ability of the LTE terminal-appliqué combination to estimate and compensate for the Doppler shift, and b) the ability to maintain connectivity to the network and successfully effect handovers under appropriate conditions.

The Doppler shift estimated by the appliqué was logged to enable comparison with the actual Doppler that was calculated by processing the location estimates provided by the GPS device collocated with the LTE terminal. Note that the appliqué always determined the Doppler shift for the serving eNB. Thus, as the LTE device was handed over between the two eNBs, it provided the Doppler shift for one or the other of the two eNBs.

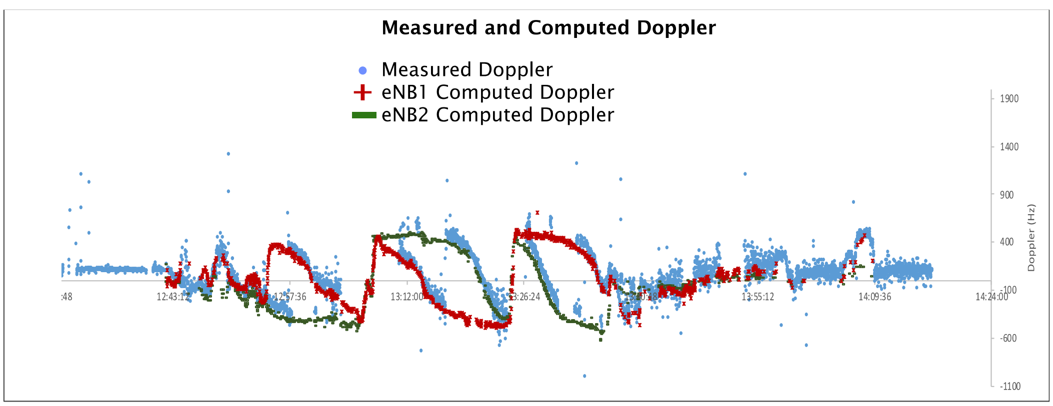

Figure 9: A Segment of the Actual and Estimated Doppler Shifts Recorded During the Field Test

Figure 9 shows a small segment of Doppler measurements as functions of time. The red and green curves respectively show the actual Doppler shifts for eNB 1 and eNB 2. The blue curve shows the Doppler shift with respect to the currently serving eNB as estimated by the appliqué. Although the Doppler shifts are not particularly large because of the limitations on the speed placed by the terrestrial nature of the transport vehicle (car), it is easy to see that the appliqué is very accurate in its estimate of the Doppler shift with respect to the currently serving eNB. Note that the jumps in the "blue curve" occur when the LTE terminal is handed over from one eNB to the other. It is clear from the figure that no matter which of the two eNBs is connected to the terminal, the estimate of the Doppler is accurate. One can also see a few gaps in the "blue curve." These gaps correspond to the periods when the radio link was lost due to extreme shadowing. Barring these expected occurrences due to the terrain, the LTE terminal was able to maintain connection to the network throughout the tests, executing handovers whenever the conditions required them.

CONCLUSION

High Doppler shifts between base stations and TAs constitute the biggest hurdle in the successful implementation of AMT based on the LTE cellular technology. We have developed a solution to this problem that uses an appliqué to estimate and compensate for the Doppler shift on the uplink signals. In this paper, we described the laboratory and field test setups that have been used to test the performance of our proposed appliqué-based solution under different operating conditions. We also presented several results of the tests that have been carried out using the laboratory and field test setups. These results affirm the viability of our solution to the problem of high Doppler shifts in airborne AMT.

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REFERENCES

[1] Achilles Kogiantis, Kiran Rege, Anthony A. Triolo, "LTE System Architecture for Coverage and Doppler Reduction in Range Telemetry," *International Telemetering Conference (ITC 2017),* Las Vegas, NV, November 2017

[2] William H. Johnson and Kiran M. Rege, "Doppler Compensation for LTE-Based Aeronautical Mobile Telemetry," 22nd Test and Training Instrumentation Workshop, (ITEA Workshop), Las Vegas NV, May 15-17 2018

[3] 3GPP TS 36.211 V10.7.0 "Physical Channels and Modulation (Release 10)," February 2013.

[4] Sebastian Caban, Christian Mehlfuhrer, Markus Rupp, and Martin Wrulich, *Evaluation of HSDPA and LTE: From Testbed Measurements to System Level Performance,* Chapter 9, John Wiley & Sons, November 2011.