A Methodology for Repeatable, Off-line, Closed-loop Wireless Communication System Measurements at Very High Velocities of up to 560 km/h

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***Abstract*—The impact of high velocities on the physical layer downlink performance of mobile radio communication systems is generally measured by placing a receiver in a car, train, or similar vehicle. While these so-called drive test measurements produce valuable results, they lack the flexibility, repeatability, and controllability usually required for initial testing of ideas and algorithms.**

In this paper, we present a methodology that allows for repeatable, closed-loop, off-line-processed measurements at velocities up to 560 km/h (350 mph). The proposed laboratory set-up allows for precise controlling of velocity and average signal-to-noise ratio. For increased convenience during initial testing, the apparatus can be even used indoors.

I. INTRODUCTION

Nowadays, there is an increasing demand for wireless services in high-speed vehicles, as for example in new generation trains. Implementing wireless applications suitable for high-speed conditions requires the adaptation of existing wireless protocols and applications to guarantee a reliable service. For example, in [1] the authors work with faster handover protocols than the ones currently used in GSM (250 km/h) and UMTS[1]. Additionally, fast IP handover improvements allowing for Internet services in high-speed trains are studied in [2] by means of a combination of a geo-satellite network and a terrestrial wireless local area network. In [3], a reliable communication-based train control to improve track utilization and enhance train safety is introduced. A system demonstrator is proposed in [4] with the objective of providing all available UMTS services to train passengers as well as allowing for control and signaling train applications.

On the other hand, [5] and [6] evaluate both, performance and propagation characteristics of wireless communications in high-speed trains, studying factors such as speed, waveguide effects in closed (narrow) environments, propagation loss affected by waves re-entering the car through train windows, and propagation loss among train cars. Finally, harmonic characteristics of Korean high-speed trains using power electronics equipment such as converter-driven motor drives, battery chargers, or auxiliary power supplies are analyzed in [7].

The aforementioned studies contribute to the inclusion of new wireless services in high-speed vehicles. In this sense, this paper proposes a methodology that allows for repeatable, closed-loop, off-line-processed measurements at very high velocities (up to 560 km/h), exceeding the speed limits of current wireless communication standards (500 km/h for GSM-R[2] [8] and for LTE[3] [9, p. 4]). Nonetheless, note that directly evaluating the performance of mobile wireless communication systems under the aforementioned conditions becomes extremely difficult in, for example, high-speed train environments.

II. TESTBED MEASUREMENTS

In principle, measuring the physical layer downlink performance of a new wireless communication system at high velocities is simple. Figure 1 shows a possible set-up where a static transmitter is mounted on a roof, and a moving receiver is placed in a car or a train:

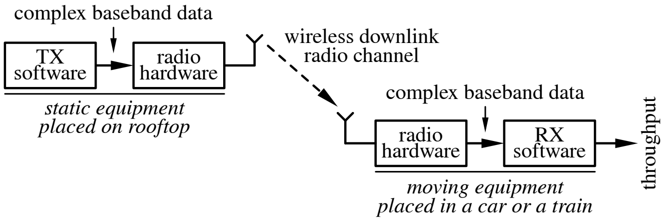

Fig. 1. Testbed measurement set-up.

Keeping things as simple as possible, the first step is to generate a representative transmit signal block (a representative statistical sample) in high-level programming environments as for example Matlab[4] or C++. The next step is to convert

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[1] GSM, Global System for Mobile Communications and UMTS, Universal Mobile Telecommunications System… mobile communication standards.

[2] GSM-Railway… mobile communication standard for railway communication.

[3] LTE, 3GPP Long Term Evolution… mobile communication standard, successor of GSM/EDGE and UMTS/HSxPA.

[4] Mathworks™ Matlab®, a numerical computing environment often used in communication engineering.

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this block into an analog, high-power signal to be transmitted over a wireless channel. Finally, at the receiver, this block is then converted back into a format that can be processed using high-level programming on a personal computer. The resulting throughput then represents the instantaneous physical layer downlink performance of the radio communication system under investigation. If the average downlink performance is of interest, one has to take a larger sample by repeating the measurement. The mean throughput performance of the scenario is then calculated by averaging all values obtained.

However, the following **difficulties** arise:

- **Code** has to be written to generate and receive standard-compliant blocks of data. Fortunately, for mobile communication standards such as LTE, free simulators exist [10]. Implementing the complete transmitter and receiver in dedicated real-time capable hardware would also be possible, yet usually too time-consuming. We therefore chose to implement all algorithms off-line in Matlab.
- The transmit and receive **radio hardware** has to be bought or built. When dealing with multiple base-stations employing multiple antennas at the transmitter site and multiple antennas at the receiver site this task is not trivial. Such endeavor consumes a lot of money as well as resources and, therefore, it is a challenge on its own (see [11]). In this paper, we utilize the Vienna MIMO Testbed developed by us from 2006 to 2009 [12].
- If carried out using a car, measurements are **neither controllable nor repeatable**. In other words, it is impossible to externally set a specific average signal to noise ratio or to drive exactly the same route twice, especially not several times a second as it may be preferred in certain measurement set-ups. We therefore refrain from measuring in a car and seek other possibilities.
- **High velocities**, as for example the 500 km/h considered for LTE [9, p. 4], present an additional challenge as trains (and other ground-based vehicles) usually fail to deliver such high speeds.
- Modern wireless communication systems employ channel adaptive modulation and coding techniques. For a measurement, this means that channel information gathered by the receiver —the so-called "**feedback** information"— has to be transmitted back to the transmitter in the uplink or via an external connection. This imposes a problem if the feedback chain consisting of receiver signal-processing, link back to the transmitter, and transmitter signal-processing is not implemented in dedicated hardware, thus does not operate in real-time.
  - A possible solution often employed (e.g., [12]) is to operate the measurement in a static environment. This is not feasible, as we want to measure while the receiver is moving at high velocities.
  - Another possible solution is to implement the feedback chain in dedicated real-time capable hardware. Such an endeavor is only feasible for large companies (e.g. [13]).

We therefore seek to employ a technique that allows for off-line signal processing, while still supporting feedback, repeatability, controllability, and measuring at high velocities.

III. ISSUES WHEN MEASURING AT HIGH VELOCITIES

A. Feedback

Consider, for example, LTE (see Figure 2): An LTE sub-frame is 1 ms long (Block C) and may use the feedback from the sub-frame 6 ms ago (Block B) [9, p. 294] while the off-line processing for the feedback itself requires e.g. 56 ms, so Block A is the closest block that can be used to calculate the feedback.

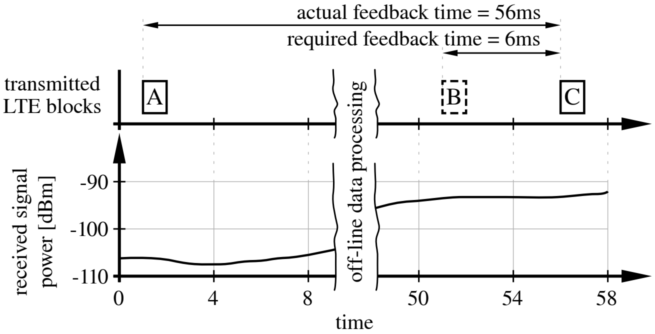

Fig. 2. Feedback in LTE.

If the channel were repeatable (equal in the left-hand and right-hand part of Figure 2) such that block A experiences the same channel as block B, off-line-processed feedback would be possible.

B. Repeatability and Controllability

To make the channel repeatable, we propose to

1) keep the surroundings constant: By carefully choosing a scenario where no objects move, this is easily possible for time spans in the magnitude of 50 ms.
2) mount the receiver on, for example, a linear guide: Accelerated by a direct-drive linear motor, accelerations of 10 g can be easily reached (g=9,81m/s^2) such that a 2.5 m long guide is sufficient to accelerate to a speed of 14 m/s (50 km/h, 31 mph) and stop afterwards.

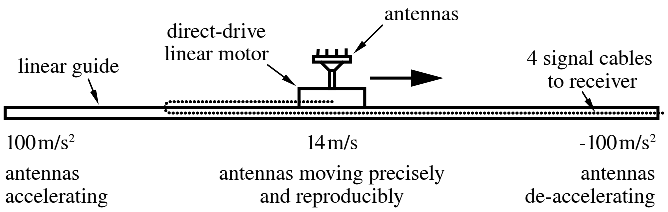

Fig. 3. Proposed set-up for low-velocity feedback measurements.

While direct-drive linear guides are precise enough to repeat a position with an accuracy of 100 μm and high accelerations can be handled by a careful mechanical design, reaching speeds greater than 20 m/s does not seem possible using off-the-shelf components. Furthermore, in the above example, it takes about half a second until the antennas are de-accelerated, moved back to the left-hand side of the guide, and then accelerated again. This minimum possible time to measure with feedback increases quadratically with the speed to be reached.

C. High Velocities

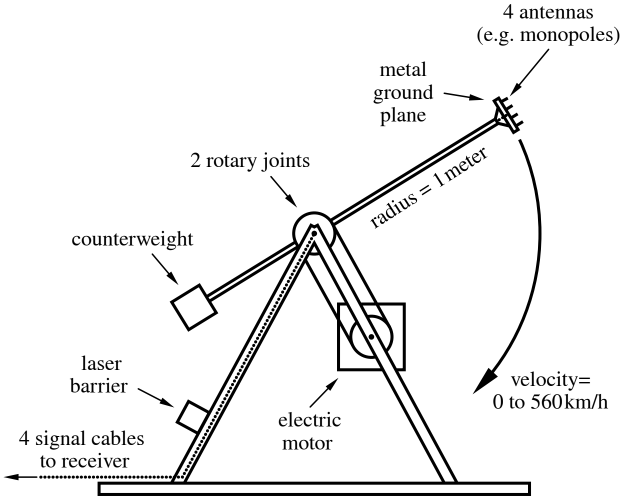

Fig. 4. Proposed set-up with fast-moving receive antennas.

At a greatly reduced price and mechanical effort, all aforementioned issues can be overcome by moving the antennas around a central pivot as shown in Figure 4. This design now allows for very high speeds while the same antenna position is still reached once per rotation.

IV. DISCUSSION OF THE SET-UP PROPOSED IN FIGURE 4

A. Applicability

While the proposed set-up can be placed at any location desired, closed-loop measurements, that is, measurements with feedback, can only be performed when the surroundings are static. In open-loop mode, measurements in any scenario are possible.

To measure the downlink of LTE at its maximum supported speed of v_{LTEmax}=139 m/s, we chose an arm length of 1 m and an electric motor that can rotate at up to 1500 revolutions per minute. At maximum speed (v=157 m/s), the antennas move about 16 cm during a 1 ms long LTE sub-frame, equivalent to 9 degrees of rotation.

Whether this set-up represents real-live situation is subject to discussion. In any case, we believe that it is useful for the initial testing of algorithms and devices in research and development as it allows for measurements that would otherwise require enormous efforts (for example measuring at 500 km/h).

B. Mechanical Considerations

In mechanical terms, the design proposed in Figure 4 is best described as a centrifuge. Rotating around a central axis at 1500 rotations per minute (f=25 rotations per second) and an arm length of r=1 m, the antenna moves at a speed of v=157 m/s (= 560 km/h = 350 mph). Therefore, the centripetal acceleration of

$$a = \omega^2 r = (2\pi f)^2 r \approx 25000\, m/s^2 \approx 2500\, g$$

has to be exerted by the arm on the antenna. Even without an antenna, to withstand this acceleration, an aluminum alloy arm must exceed a yield strength of 70 N/mm^2. To be on the safe side, we therefore chose to use a carbon fiber-reinforced polymer pipe for the arm and design all other critical parts out of high-strength aluminum alloy. A printed circuit board will act as ground plane for the antennas, while the semi-rigid coaxial radio-frequency cables required to guide the received radio waves to the receiver are glued inside the arm using fiberglass glue. The bearings, as well as the engine, can be bought off-the-shelf.

C. Electrical Considerations

Here, the critical parts are the two rotary joints that are required to connect the four rotating coaxial cables in the arm (we want our set-up to support four antennas, signal center frequency=2.5 GHz) to the static cables outside the arm. Fortunately, military-grade solutions do exist for this application. Except for the rotation, the cables itself are glued inside the arm and therefore static to not change their electrical properties due to bending. Furthermore, even while rotating, the properties of the cables can be easily checked by disconnecting the antennas and pairwise connecting the antenna ports at the end of the arm.

D. Synchronization Considerations

In order to carry out precise, repeatable measurements, the time at which the antennas will reach a distinct position has to be precisely known beforehand. We therefore utilize a high-speed laser barrier and dedicated real-time capable hardware for the timing synchronization of the blocks transmitted.

E. Validation

First, we disconnect the four antennas from the end of the arm. Then, we connect the antenna cables pairwise at the end of the arm using rigid cables. Next, we connect two antennas to the cables that come from the rotary unit. Summarizing, these two antennas are then connected to the radio frequency hardware through the proposed set-up without antennas, that is, through a looped-back “long cable” and two rotary joints.

Using this set-up, we then check whether the properties of the transmission change if the arm is rotating at different speeds.

F. Repeatability

Using the Vienna MIMO Testbed, we can repeat a measurement in an outdoor-to-indoor scenario with a throughput-precision of approximately 2% [14, p.29]. Rotating the antennas between successive measurements by multiples of whole rounds should not affect this precision.

G. Controllability

A major advantage of the proposed set-up is controllability. One can easily externally change and set the average signal to noise ratio (by changing the power of the transmitter) or the velocity (by changing the rotation speed using a frequency inverter).

H. Measurement Repetition Rate

Another advantage of the set-up proposed is the ability to carry out many measurements in short time-spans at similar or even equal conditions. Measuring, for example, in a train at 300 km/h would only allow for a few measurements until the train has passed the transmitter, and only for one measurement at a specific position.

Using the proposed set-up, several measurements can be carried out during one rotation of the arm, and measurements at equal channel conditions can be carried out once per rotation. At 300 km/h, for example, a measurement can be repeated every 75 ms. (An increased repetition rate can be achieved by reducing the length of the arm rotated.)

I. High Velocities

Future applications in high-speed trains may require algorithms to work at speeds up to 500 km/h. Unfortunately, trains or other ground-based vehicles currently do not support such high speeds. The set-up proposed in Figure 4 is designed to support velocities of up to 560 km/h.

V. EXEMPLARY MEASUREMENT ENVIRONMENT

To carry out repeatable, off-line testbed measurements we propose the measurement environment shown in Figure 5:

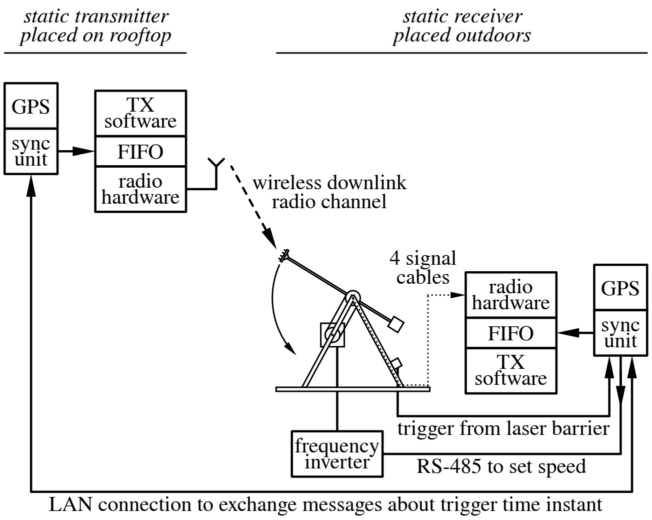

Fig. 5. Proposed testbed set-up for measuring at very high velocities.

In this measurement environment, a data block to be transmitted is first created off-line in software. Next, this block is loaded into a real-time capable transmit FIFO[5] that waits for a trigger pulse of a synchronization unit before forwarding the data samples to the radio hardware.

At the receiver, the incoming signals are captured by four antennas moving at very high-speed, next guided through coaxial cables inside the arm of the rotary unit to its axis, then guided through the rotary joints, then guided to the radio hardware and finally converted to the digital domain. In case the synchronization unit at the receiver issues a trigger, the digital data samples are stored in a FIFO buffers to be then evaluated off-line in software.

The speed of the rotary unit is controlled via RS-485 using an off-the-shelf frequency inverter. Once rotating, the arm passes once per rotation through a laser barrier that sends a pulse to the sync unit. The synchronization unit itself can use this information to exactly calculate the position of the arm. As the synchronization units of the transmitter and the receiver are locked to a GPS reference and connected to each other by a local area network connection, a synchronous trigger pulse can be issued at transmitter and receiver at always the same arm position (that is reached once per rotation). More details on how to build the therefore needed synchronization unit can be found in [15, 16].

VI. CONCLUSIONS

In this paper we present a novel way to measure the performance of mobile radio transmissions at high speeds. In contrast to drive-test measurements, our set-up allows for repeatable, off-line, closed-loop measurements at velocities exceeding 500 km/h.

We see the applicability of the proposed set-up not in the final evaluation of mobile communication devices (namely cell phones) at high speeds, but in the initial testing of parts of them and algorithms under conditions, that would otherwise require way too high efforts.

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[5] FIFO, First Iin First Out… a buffer that is filled from the input side slowly with data and then replays this data on the output side in real-time.

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