System Design and Implementation of Seamless Handover Support Enabling Real-Time Telemetry Applications for Highly Mobile Users

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ABSTRACT

IEEE 802.11 is one of the most mature WLAN technologies and system components are available at very low cost. This makes it prevealing to reuse 802.11 (hardware) components for system designs apart from traditional WLAN application areas and environments. This paper presents a novel predictive fast handover protocol enabling seamless handover support for real-time telemetry applications for highly mobile users. The employed system architecture is based on 802.11 commercial off-the-shelf components with a modified firmware. We conduct a performance evaluation using a proof-of-concept implementation. The employed methodology and metric is for the first time in strict accordance the proposed approach of the IEEE standard on wireless performance prediction. Results show that the handover delay is below 1 ms.

Categories and Subject Descriptors

C.3 [**Computer Systems Organization**]: Special-Purpose and Application-Bases Systems—*real-time and embedded systems*; C.4 [**Computer Systems Organization**]: Performance of Systems—*fault tolerance, reliability, availability, and serviceability, measurement techniques, performance attributes*; H.4 [**Information Systems Applications**]: Miscellaneous; J.7 [**Computer Application**]: Computers in other Systems—*command and control, industrial control, process control, real time*

General Terms

Measurement, Performance, Reliability

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Keywords

Fast Handover, Predictive Handover, Seamless Mobility, Telemetry, High Velocity, IEEE 802.11, WLAN

1. INTRODUCTION

As being the predominant wireless local area network (WLAN) technology, IEEE 802.11 devices have matured in reliability and are available at a cost making it most prevailing to deploy them for other application areas not considered as a typical WLAN environment so far. This trend began a few years ago by incorporating 802.11 equipment into car-to-car networks and standardizing protocols specific to the automotive environment by the IEEE [4]. They propose enhancements to the 802.11 MAC to satisfy the constraints of a vehicular environment while giving up partial backward compatibility to existing 802.11a/b/g/n devices if they were to operate in the same frequency band. But other application areas, e.g., telemetry services for remote based train control, aim at employing 802.11 components in their communication systems as well. Hereby, seamless, horizontal mobility support is *the* crucial aspect and has to cope with acceptable jitter and roundtrip delay requirements of $\ll 10$ ms and $\ll 100$ ms representing middle and high real time requirements [27]. Even though supported velocities are currently considered having an upper limit of approximately 600 km/h [15], previous work has shown that not the absolute speed of the mobile but its relative speed with respect to the coverage area of the radio cell is one key parameter for seamless mobility support [12, 10, 11]. Hence, even pedestrian mobility can impose stringent constrains to the handover process if experienced in micro- or macro-cellular environments which are currently considered for next generation WLAN systems by the IEEE 802.11 working group [21, 22].

This paper presents the design and prototype-based performance evaluation of a system providing seamless communication for vehicles traveling at high speed up to several hundred kilometers per hour. The system employs commercial off-the-shelf 802.11 components with modified firmware enabling an expected handover delay of less than 1 ms. Aligning parts of the design with previous work, the paper's novelties are:

- the explicit consideration of the requirements of highly mobile users;

- the design and implementation of a predictive fast handover protocol enabling seamless handover between homogeneous wireless networks operating on different frequencies;
- the performance evaluation of the proposed protocol and system architecture using a proof-of-concept implementation and real-channel trace from a high-speed trains scenario;
- metric design in accordance to the IEEE recommended practice for wireless performance prediction [3].

The remainder of the paper is structured as follows: Section 2 summarizes related work on improving the handover performance for 802.11-based systems. Section 3 sketches the system concept and design followed by a description of the Fast Handover Protocol and the implementation of a proof-of-concept demonstrator. Finally, Section 6 presents the performance evaluation of our proposed system architecture including the predictive fast handover protocol.

2. BACKGROUND AND RELATED WORK

The handover process, in general, requires the following four functionalities: network discovery (probing), handover decision and involved decision criteria, link layer reestablishment, and, if necessary, higher layer procedures. All these functions do not occur in a strict sequence, but may also overlap or even happen in parallel [13]. Additionally, a preceding detection of the need to conduct a handover sums to the associated delays [26]. Empirical analyses indicate that detection accounts for up to 1000 ms and network discovery using optimized active probing for approximately $150-200$ ms. Link layer reassociation can be conducted within $3-4.5$ ms [20, 26, 2].

The main problem when using WLAN for telemetry applications for highly mobile users are twofold: first, the acceptable handover delay is already in the order of *single handover phase*, e.g. the re-association. Second, the dwell time in the overlap of adjacent cells is too small to trigger and complete the handover process. Even though research investigated approaches reducing one or several handover phases, the latter aspect has not been considered thoroughly in the evaluation of proposed schemes:

Only a few authors assessed the detection phase. Velayos and Karlsson [26] propose to use the absence of n consecutively lost beacons as an indication for connectivity loss. Therefore, they characterizes the probability of missing n beacons due to collisions rather than having left the coverage are of an access point (AP). While this approach reduces the duration phase to the order of the target beacon transmission time, other authors determined the minimum required overlap of adjacent cells to expunge the detection phase using radio signal strength measurements [28, 29, 10, 11, 12].

Regarding network discovery (probing) being the most intensively studied handover phase, we only summarize most novel research resulting in the best known, published reduction of its duration. Shin, Mishra, and Arbaugh [24] employ graphs representing the neighborhood between access points in order to reduce the number of channels to be scanned when a station loses connectivity to its current AP. Apart from static preconfiguration, they show how stations' (STAs') movements can be used to derive the graph by recording the handover between two APs. Their approach can reduce the probing time of a *single* channel in between $1.8-11$ ms while for a typical, regular cell deployment using three non-overlapping frequencies the discovery phase reduces to an expected mean of 7.3 ms. Another approach presented by Ramani and Savage [23] moves the network discovery phase a prior the actual handover. Their SyncScan algorithm continuously tracks nearby access points by synchronizing short listening periods at the client with the periodic transmission of beacons of neighboring APs. To avoid packet loss during these scanning attempts, the AP and STA buffer user data in the meantime; hence experiencing a very frequently occurring delay which the authors quantify in the order of 15 ms. Singh, Atwal and Sohi [25] as well as Chui and Yue [9] extend the SyncScan approach and present access point coordination and signaling schemes providing a (distributed) approach to synchronize beacon transmissions within a given time period for all APs in the distribution system operating on the same channel. Their work, however, does not affect the delay associated with the handover process. While the original SyncScan algorithm only knows when a beacon of any AP *should* be transmitted, STAs still attempt to scan for beacons of APs even if they are not within the latter's coverage. DeuceScan presented by Chen et al. [8, 7] combines neighborhood graphs with SyncScan hence reducing the scan attempts to channels where the probability to receive a beacon is high. Additionally, they use (geographic) position information of APs to estimate the mobile's movement based on the radio signal strength indicator (RSSI) received from APs. Based on simulation results, DeuceScan can reduce the associated service interruption up to 3.5 ms which corresponds to the transmission time of an IEEE 802.11 probe request presumably not considering the channel switching time adding an additional delay of 10 *ms* as observed by [23].

Amir et al. [5] present an approach to expunge the link reestablishment (authentication and association) phase for a wireless mesh network in which *all* APs operate on the same frequency. APs employ a multicast-based signaling over the distribution system to exchange information if a STA is within the overlapping area of several APs. Based on signal strength measurements, the AP which is the most likely handover candidate transmits data destined to the STA in addition to the AP currently serving the latter. Hence, the STA receives duplicate packets while in the overlapping area and can smoothly transition from one AP to another. As all APs operate on the same frequency, the process is transparent to the STA and channel switching as well as network discovery are omitted and a delay is not noticeable. For this reactive approach, presented measurements indicate that STAs are within the overlap for approximately $2-3$ seconds which is only feasible for low or moderate user mobility.

Table 1 summarizes the delays for different handover phases. Please note that the only approach providing a total handover delay of less than 10 ms neither supports multiple-frequency networks nor high mobility scenarios due to its reactive approach. This indicates, that a predictive handover approach can satisfy the requirements for telemetry applications for highly mobile users as it can reduce the experienced handover delay to the mere channel switching time of the radio transceiver. At the same time, it allows to re-

Table 1: Achievable Delay per Handover Phase – State of the Art

Ref.	Detection	Network Discovery	Decision	Link Re-Establishment
[28, 29] [10, 11] [12]	0 ms	n/a	0 ms	n/a
[8, 7]	3.5 ms (plus 10 ms for channel switch)			
[5]	$\ll$ 10 ms (only single frequency networks; low user mobility)			n/a

duce the dwell time of the mobile in the overlapping area of cells either to the bare minimum for radio signal strength based handover trigger [12, 10, 11] or even further for location based handover decisions.

3. SYSTEM CONCEPT AND DESIGN

3.1 Requirements & Assumptions

In order to provide telemetry services for highly mobile (vehicular) users, handover latencies have to be well below 10 ms with guaranteed media access times. Considering users' velocity and the coverage area of a single radio cell, the expected mean dwell time in a radio cell is less than 10 seconds. Hence, the time spent in the overlap of adjacent cells is neglectfully small [16, 15]. Also, mobile devices have only one network interface card (NIC) which is a feasible assumption to reduce system cost for mass deployment.

3.2 System Architecture

The proposed architecture consist of a micro / macro cellular system. Several micro cells operating on the same frequency are grouped into one macro cell such that adjacent macro cells operate on non-interfering channels. Micro cells are physically formed by spatially distributed remote base stations (RBSs) whereby a centralized radio control unit (RCU) coordinates interference free medium access among them. A distribution system (DS) connects the RCUs and associated macro cells among each other as well as to the DS Portal acting as a gateway to the Internet. RCU and RBS are standard PCs running Linux where an IEEE 802.11 NIC with modified firmware builds the wireless interface of each RBS. The modified firmware simply bridges packets received from the RCU to the wireless interface and vice versa thus abandoning the stochastic 802.11 distributed coordination function. A dedicated backbone achieves the spatial distribution of the RBSs. We herein use a transparent layer-3 connection between RCU and any of its RBSs' to tunnel communication between the latter over Ethernet.[1] Also, the Precision Time Protocol IEEE 1588 [1] synchronizes their local clocks to give an estimation of the forwarding delay with an accuracy of a few micro seconds [17]. Without loss of generality, Fig. 1 illustrates one exemplification of the system architecture.

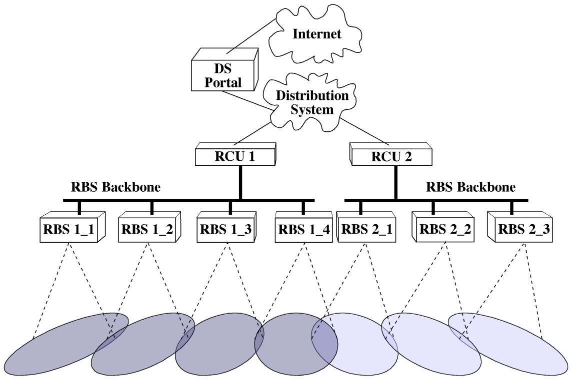

Figure 1: System Architecture for Fast and Seamless Handover Support

3.3 MAC Scheme

The RCU imposes a deterministic TDMA with its macro cell by regularly scheduling downlink transmission; the mobile may respond immediately after the reception of a downlink packet. Transmissions are upper bounded by a fixed (transmission slot) length. In case the RCU does not have pending downlink traffic for a mobile, it polls the latter within the scheduled transmission slot. If no uplink traffic is pending, the mobile sends a pilot signal allowing the RBS to assess the current link quality. Also, each n slots, the RCU announces a random medium access period. Mobiles may therein employ the 802.11 DCF to signal their presence to the DRCU requesting an initial slot assignment during association. IEEE 802.11 framing and addressing as provided by the commercial off-the-shelf NIC cards is used for the actual transmission.

4. FAST HANDOVER PROTOCOL

4.1 Intra-Macro-Cell Handover

The handover process within a macro cell is transparent to the mobile user and does not require any signaling via the wireless media: As all RBSs within a macro cell operate on the same frequency, uplink traffic may be received by more than one RBS if a mobile is within the overlap of their coverage area. For each received packet, the RBS forwards the received radio signal strength along with the packet to the RCU which in turn may choose on a packet to packet base the RBS to be used for the next transmission. In general, this approach resembles the one presented in [5] but does not require the mobile to reside within the overlap of adjacent micro cells for a long time. Rather, the latter may be reduced to a bare minimum according to [10, 12, 11].

4.2 Inter-Macro-Cell Handover

The system requirements regarding the handover delay are already in the order of the channel switch time and the time of the link layer reestablishment (c.f. Section 3.1 and Table 1). Accordingly, the predictive fast handover approach avoids all of the traditionally known handover phases.

The RCU inherently tracks the mobile's movement with

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[1] Alternatively, we have shown in [18] that a corresponding architecture can also be built using radio-over-fiber-based components.

its macro cell and hence detects when a mobile enters the boundary of the macro cell. The boundary is thereby defined as a micro cell which overlaps with a micro cell of another marco cell. RBS_1_4 and RBS_2_1 in Fig. 1 represent, e.g., such a boundary. Upon a mobile entering the boundary of a macro cell, the latter's RCU signals the neighboring RCU via the DS that a handover might be inherent and that the neighbor RCU shall *predictively* start transmitting downlink traffic destined for the mobile. At the same time, the RCU signals the frequency allocated to the neighboring macro cell to the mobile. Doing so, the mobile may decide to handover to the neighbor macro cell by observing the current radio signal strength. This decision scheme itself does not add any handover latency [10]. Once switching to the new frequency, the mobile immediately receives downlink traffic and may transmit upload traffic without any prior link reestablishment. Two aspects remain to be solved: how to gain knowledge on the neighborhood of adjacent micro cells of different macro cells; and how to achieve that traffic for the mobile is received simultaneously by all involved RCUs during the predictive handover phase.

The neighborhood knowledge may either be pre-configured or dynamically learned by mobiles signaling a failed fast handover in combination with information on the RCU serving the mobile a priori the handover. Other schemes [24, 8, 7] adopting neighbor graphs in combination with movement prediction may also be applied.

A multicast based approach is employed to assure that mobile specific traffic is received by all involved RCUs. We therefore assign a unique multicast MAC address to each mobile during its initial association to the system. This MAC address in combination with the mobile's IP address is signaled to the DS Portal. The latter in turn manipulates its ARP tables to use the multicast MAC address to forward *any* traffic for the mobile. During the predictive fast handover phase, involved RCUs subscribe to the associated multicast group using the Generic Attribute Registration Protocol (GARP) or Multicast Registration Protocol (GMRP) which is regularly available in commercial off-the-shelf switches and routers. Such multicast based approaches have been intensively studied in [14], reused in [5] and are known not to add any handover latency.

5. PROOF-OF-CONCEPT DEMONSTRATOR

All system components, i.e. the Predictive Fast Handover Protocol enabling inter-macro-cell handover, the scheduler at the RCU imposing a deterministic media access, the modified firmware running on the 802.11 NIC have been specified in SDL, verified for correct functional behavior, and tested against deadlocks using Telelogic's SDT. Runtime code for our proof-of-concept demonstrator is automatically generated from the SDL-based specification as described in [19]. We acknowledge that focus was herein rather set to implement verified functionalities of the system components rather than optimizing the code for performance.

The prototype system corresponds to a subset of the architecture illustrated in Fig. 1 only containing three micro cells (RBS_1_3, RBS_1_4, and RBS_2_1). Additionally, we connect a Linux system via the DS Portal to our testbed functioning as a source / destination for UDP-based probe traffic which is later on used to evaluate the handover performance.

A single mobile client is added to the system. All the involved wireless cards are connected to a channel emulator which allows to impose a stochastic channel model between any two pairs of transmitters / receivers. Also, the channel characteristic can be adjusted according to prerecorded channel traces deriving from a real world system.

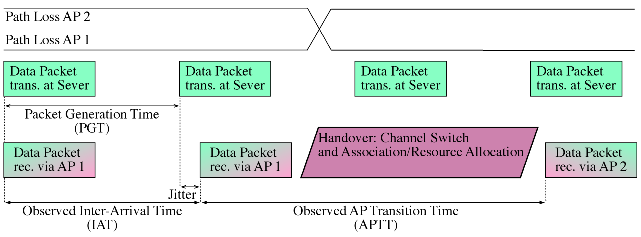

Figure 2: Access Point Transition Time Performance Metric according to IEEE P802.11.2

6. PERFORMANCE EVALUATION

In order to evaluate the performance of the proposed support for fast handover, we use the proof-of-concept implementation (c.f. Section 5) to assess the handover delay a.k.a access point transition time. The used metrics are introduced first followed by the empirical evaluation of the access point transition time / handover delay.

6.1 Access Point Transition Time Metric

In order to classify the performance of (end-) systems–including applicable protocols supporting fast handover–the IEEE decided to measure the *access point transition time* (APTT) of the handover process [3, 6]. The standard defines the transition time as the interim between the last successful transmission/reception of a data frame via the origination AP (here RBS) and the first successful transmission/reception of a date frame via the destination AP (here RBS) as illustrated in Fig. 2. Hence, the APTT includes all the time required to establish a "working" link connection for the user, i.e., above the MAC.

Obviously, the smallest observable APTT is lower bounded by the time ($t_{switchF}$) required by the mobile to tune its radio transceiver from the frequency the originating AP operates on to the one of the destination cell. Additionally, as the successful arrival/transmission of data frames is used to trigger the measurement of the APTT, the precision of this approach depends on the inter-arrival-time (IAT) of data frames via the same AP, i.e., without experiencing a handover. Therefore, we derive in the following the theoretical minimum and maximum of the APTT.

Let μ_{IAT} and μ_{APTT} be random variables representing the measured packet-inter-arrival time (i.e., without the occurrence of a handover), and the access point transition time. $E\{\cdot\}$, $Max\{\cdot\}$, and $Min\{\cdot\}$ denote correspondingly to the expected mean, maximum, and minimum value.

As the handover–i.e., switching from the old to the new transmission frequency–occurs randomly, a single packet might be lost during the handover if it is transmitted immediately after the mobile started the handover hence being in the phase of retuning its radio transceiver. Assuming synchronized packet transmissions at the old and new AP, we derive–as illustrated in Fig. 3–the theoretical minimum and

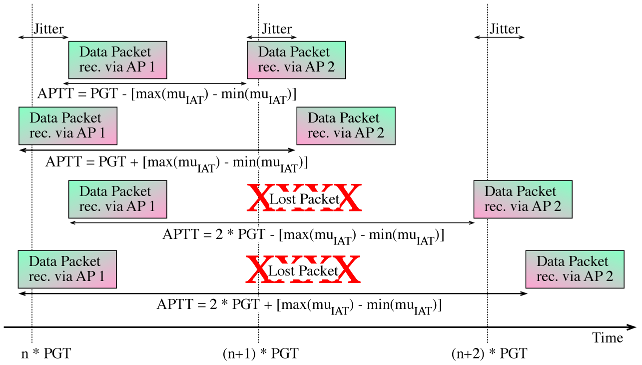

Figure 3: Deriving the Theoretical Minimum and Maximum of the APTT

maximum of the APTT:

$$\varepsilon := Max\{\mu_{IAT}\} - Min\{\mu_{IAT}\}$$

$$Min\{\mu_{APTT}\} = E\{\mu_{IAT}\} - \varepsilon \tag{1}$$

$$Max\{\mu_{APTT}\} = 2 * E\{\mu_{IAT}\} + \varepsilon \tag{2}$$

For asynchronous transmissions of packets at the involved APs, Eq. 1 simplifies to

$$Min\{\mu_{APTT}\} = t_{switchF} \tag{3}$$

as the handover could occur immediately after the reception of a packet via the originating AP and right before the destination AP transmits another one. As these upper and lower limits of the APTT are based on a worst case error propagation, we do expect the measured APTTs to be well within these limits.

In addition to the APTT metric, we define the (mean) handover delay (HOD) as

$$HOD := E\{\mu_{APTT}\} - E\{\mu_{IAT}\} \tag{4}$$

which hence represents how long a packet after an handover is delayed from its (expected mean) time of arrival in the absence of a handover.

6.2 Empirical Evaluation of APTTs

6.2.1 Experiment Setup

We emulate the movement of the mobile terminal by changing the attenuation between each transceiver pair connected to the channel emulator such as if the mobile moved from RBS 1_3 through RBS 1_4 to RBS 2_1 and vice versa. The imposed attenuation pattern is based on measurements of the radio signal strength of the radio signal between the Transrapid high speed train and radio base stations along its trail (c.f. Fig. 4(a)). The experienced signal is subject to severe deep, short term fades as exemplarily illustrated in Fig. 4(b). As the used channel emulator requires an attenuation pattern given in dB as an input, we use the 10th-degree approximation of the transceiver characteristic as shown in Fig. 5 to convert the measured RSSI values. The chosen degree of the approximation function results in an error of less than 1% over the RSSI range from 0.5 to 1.5 which is relevant for handover decisions. Also, it almost perfectly approximates the power drop off at the receiver's sensitivity level hence given a reasonable compromise between accuracy and computational complexity of higher degree approximations. The channel emulator uses the approximation function to convert empirical RSSI values and stops forwarding packets to any connected card if the experienced attenuation at the receiver falls below -80 dBm. The mobile initiates a handover once the received signal falls below -77 dBm–hence employing a 3 dBm hysteresis margin. The overlap of adjacent macro cells is calculated according to [10, 12] whereas the overlap of RBSs belonging to the same macro cell is merely large enough to ensure a signal reception above the -77 dBm handover trigger.

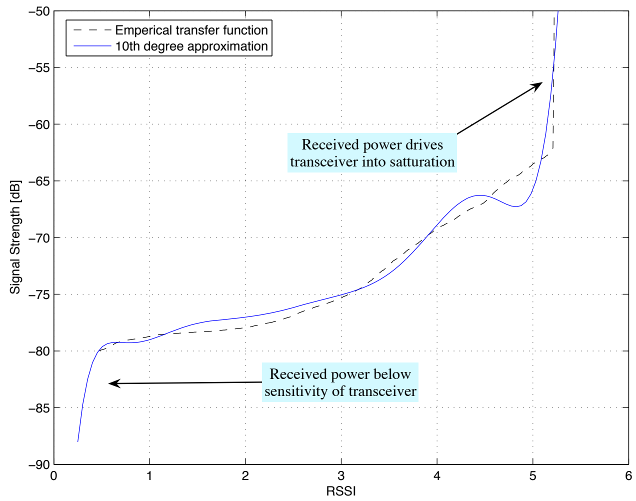

Figure 5: RSSI Characteristic of Transceiver

6.2.2 Measurement Results

The first measurements quantify the IATs while the mobile resides within one macro cell.[2] Even though the expected mean ($E\{\mu_{IAT}\} = 5.01$ ms) does not significantly differ from the 5.00 ms time interval at which the packets are generated at the server, the IATs cumulative distribution function in Fig. 6 shows two anomalies, namely a median of 5.36 ms and a probability of 8% that consecutive packets arrive within 0.03 ms. These two phenomena can be explained as followed: Since all the protocol components of the proof-of-concept demonstrator–including the bridge connecting the ethernet interface of the RBS backbone to the wireless interface as well as the bridge between RBS backbone and distribution system at the RCU–run in the user space, we noticed that we reached the capacity limits of our implementation imposing a forwarding load of 200 $packets/s$. A further increase of the load resulted in unpredictable packet losses. As a result, our MAC process is regularly interrupted by kernel threads and hence cannot provide a "real time scheduling" of packets to be sent to the wireless system at a peaceful five millisecond-rate. As packets arrive faster than the MAC can schedule transmission time slots, we see two packets residing in the transmission queue after every 10th transmitted packet. As the MAC transmission slots per mobile are large enough to hold more than one packet, the MAC forwards the two packets in the

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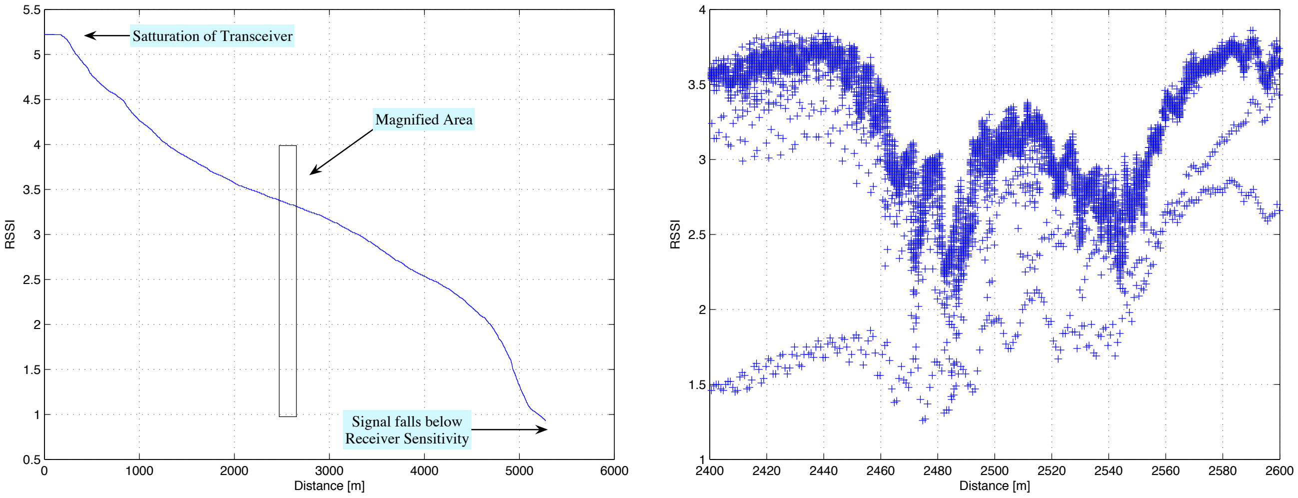
[2] Please note that the results for a stationary mobile and a mobile only moving between RBSs of the same macro cell do not differ and are not separately discussed.



(a) Moving Average of RSSI Samples (b) Magnification showing actual RSSI samples

Figure 4: Empirical Radio Signal Strength over Distance

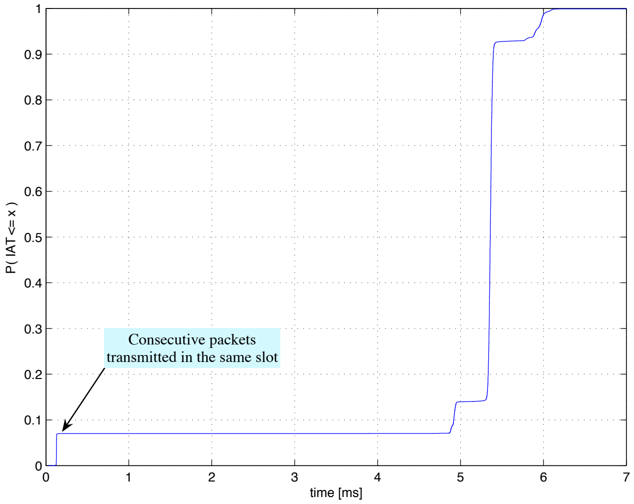


Figure 6: Packet Inter-Arrival Times (empirical CDF, without handovers, targeted $PGT = 5$ ms)

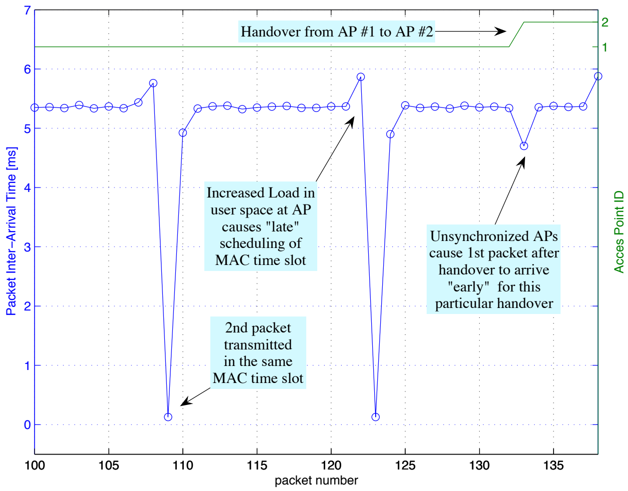


Figure 7: Packet Inter-Arrival Times before and after Handover

queue within the same MAC time slot. Hence, the IAT of these two (data) packets is recorded to be 0.03 ms. Figure 7 illustrates this situation occurring for packet numbers 108/109 and 122/123. As a MAC frame (in this specific case holding two data packets) is either correctly received in its whole or entirely discarded, these short IATs cannot be experienced during an inter-macro-cell handover and hence have to be discarded when calculating the theoretical minimum and maximum APTT according to Eq. (1), (2), and (4). Table 2 summarizes the corresponding statistical properties of the IATs for the recorded raw data and if the IATs belonging to packets received within the same MAC time slot were discarded.

Based on the assessment of the IATs, we derive according to (2) and (3) the theoretical lower and upper bound for the APTTs coping with a worst case propagation of errors. As macro cells transmitting their MAC time slots

Table 2: Statistical Properties of Packet Inter-Arrival Times (without handovers, targeted $PGT = 5$ ms)

	Raw Data	Deleted IATs corresponding to packets transmitted within the same MAC time slot
$E\{\mu_{IAT}\}$	5.01 ms	5.37 ms
$Min\{\mu_{IAT}\}$	0.03 ms	4.86 ms
$Max\{\mu_{IAT}\}$	6.27 ms	dito

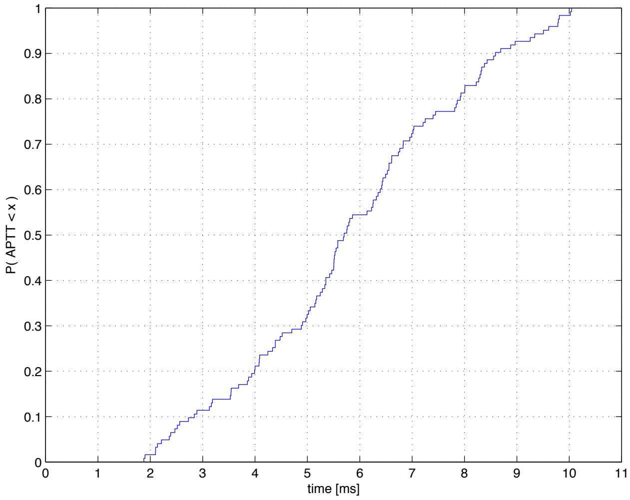


Figure 8: Access Point Transition Times (empirical CDF, $E\{IAT_{noHO}\} = 5$ ms)

asynchronously, we obtain $Max\{\mu_{APTT}\} = 12.15$ ms and $Min\{\mu_{APTT}\} = 1.70$ ms. Herein, $t_{switchF}$ is again a measurement based value accounting for interim between indicating the MAC board to switch its operating frequency up to the time the latter confirms success and is hence ready for a new transmission of user data.[3]

Figure 8 depicts the empirical CDF of the APTTs. The samples are uniformly distributed between 1.88 ms up to 10.04 ms which meets our expectations as two neighboring macro cells are not synchronized regarding the transmission of MAC time slots. The theoretical lower bound is only missed by 0.18 ms whereas the upper bound accounting for a worst case error propagation was set too conservatively. As the lower bound is determined by the time interval in which the mobile's radio is switched from one frequency to another (including processing overhead due to the firmware and operation system implementations), the mobile cannot receive or transmit packets during this time. Hence, we should experience a packet loss. We observe that the probability to lose exactly one packet is 22% as shown in Fig. 9. Notable, this is in the same order as relation of the frequency switching time to the maximum observed APTT ($Min\{\mu_{APTT}\}/Max\{\mu_{APTT}\} = 19\%$). Also note that in 10% of the cases, a single data packet is received twice, once via the originating cell before the handover and once via the designating cell afterwards. As expected, the probability to guarantee packet losses ≤ 1 is 100%.

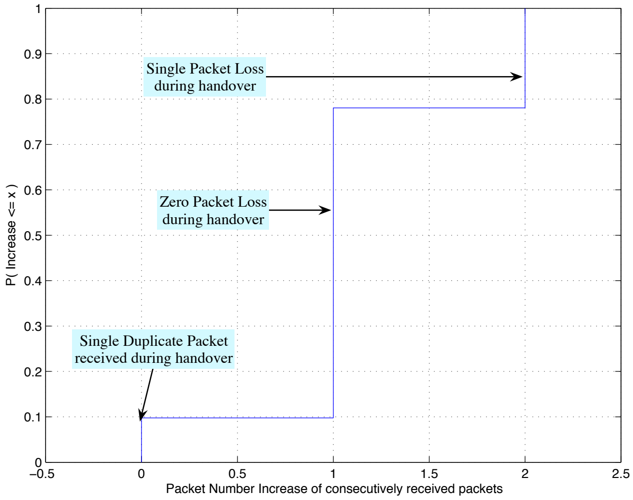


Figure 9: Packet Loss During Handover

Finally, we use the empirical results to calculate the handover delay according to (4):

$$\begin{aligned} HOD &:= E\{\mu_{APTT}\} - E\{\mu_{IAT}\} \\ &= (5.84 - 5.37)\ \text{ms} = 0.47\ \text{ms} \end{aligned}$$

7. CONCLUSION AND SUMMARY

This paper presented a summary of the most recent advances in research to provide low handover latencies. We hereby show that non of the existing schemes employing commercial 802.11-based devices can satisfy the handover requirements for telemetry applications for highly mobile users. Accordingly, this paper proposes a predictive fast handover protocol and combine it with existing approaches for fast handover support. We evaluate our approach using a proof of concept demonstrator and real channel traces showing that the remaining handover delay of less than 1 ms. The employed methodology and metric design for the evaluation are for the first time in strict accordance to the IEEE standard for Wireless Performance Prediction and hence allow a comparison of our system design with other, future commercial system architectures.

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