Handovers in Wireless ATM Networks: In-Band Signaling Protocols and Performance Analysis

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Abstract—**The first part of this paper presents a novel scheme for handover provisioning in Wireless ATM (W–ATM) networks based on in-band signaling. First, the network architecture and principles of in-band signaling are described, discussing advantages and interaction with other procedures and signaling techniques. Then, loss-free protocols for the handover procedures are presented and compared with existing proposals. The second part of the paper is devoted to performance analysis of the handover procedures. A general methodology for evaluating handover delays and required buffer capacity is introduced and exemplified for one of the protocols introduced before. Numerical results give insight into the handover procedure characteristics and are compared with estimates provided by detailed discrete event simulations for validation purposes. Finally, additional simulation results are presented for parallel, concurrent handovers, evaluating the requirements posed to the network by different handover procedures.**

Keywords— **Wireless ATM, handover procedure, performance evaluation.**

I. INTRODUCTION AND MOTIVATIONS

Mobile communications are now mature to offer packet switched and broadband services. GPRS (General Packet Radio Service) [1], [2] will be offered soon in Europe, WAP (Wireless Application Protocol) sites start offering WWW access to mobile terminals that have the size of a normal mobile phone, while UMTS (Universal Mobile Telecommunication System) licenses are being auctioned by Governments. The activities of the main standardization bodies, like ITU–T, ETSI and ATM Forum, on the next generation cellular systems are all characterized by the clear aim to provide multimedia services, with the ability to support connections at 2 Mbit/s and above. Specific research projects like those described in [3], [4], [5], [6] are studying and prototyping large bandwidth (up to 25 Mbit/s) cellular networks, integrated within B-ISDN, shaking the traditional idea that mobile networks must be narrowband and specialized. Similar works concentrate on the integration of mobility within the TCP/IP Internet protocol suite [7].

The requirements posed by standards, and the relevant future role of data services, are hints to the fact that one of the candidate technologies for cellular systems integrated within B-ISDN is ATM. Two different approaches can be observed in ATM based cellular networks. The first one is supported mainly by the ATM Forum [8]; it involves the presence of ATM connections through the radio interface, up to the mobile end user. The second one, preferred by more traditional standardization bodies like ITU-T and ETSI, and reflected in IMT 2000 [9] and UMTS [10], involves the presence of ATM only in the fixed part of the mobile network, thus avoiding the transport of ATM cells over the wireless link. This paper deals with a network architecture consistent with the first approach; nevertheless, most of the work described here can be extended to the second approach with little effort. Network architectures consistent and similar to the one we consider were adopted in several papers that study the overall signaling architectures [3], [11], [12], [13].

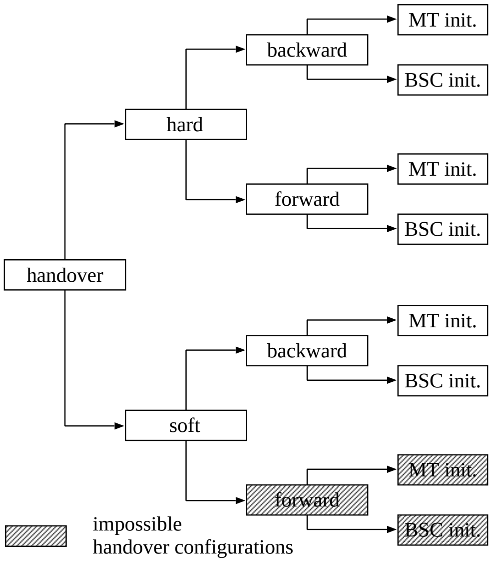

Fig. 1. Classification tree of handover procedures.

The introduction of handover procedures in ATM networks has normally a deep impact on the transport and control planes in terms of modifications to standard signaling and switching functions [11], [14]. We therefore propose the use of the in-band signaling technique, which limits these modifications since signaling related to specific procedures, like handovers, can transparently cross ATM switches that are not enhanced with mobility functions. Some modifications are still needed to manage procedures when there are no communications active.

Multi-service, packet based networks, should support several types of handover procedures, in order to provide mobility to all possible services. Fig. 1 reports a classification tree for handover procedures; the ATM Forum proposed a classification [15], [16] (whose naming we adopt here) and a similar one is reported in [17]. Also, handovers should preferably be seamless[1] in order to minimize service disruption, specially for data services.

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[1] In this work, the term *seamless* handover procedures refers to those procedures that guarantee loss-free and in-sequence delivery of cells; other authors sometimes use the same term with a different meaning.

Seamless handovers in ATM networks pose a relevant problem in the synchronization of the procedure for in-sequence cell delivery; this problem is not relevant in PCM (Pulse Code Modulation) based networks [18], [19], where the PCM frame itself can be used for synchronization. ATM networks do not have explicit means for synchronization and information re-ordering; cell headers do not contain counters and are all identical to one another. During seamless handovers, either soft or hard, a problem arises due to the implicit VC merging embedded in any handover scheme. ACTS research projects like RAINBOW [20] and Magic WAND [21] found that cell mis-ordering due to non-synchronized VC merging is common during handover, as it was also recognized in [11], [22]. The reason generally lies in different propagation and processing delays of common channel signaling messages. The use of explicit synchronization information (delimiters and packet counters) within the user data flow seems to be the only solution to the problem. The use of in-band signaling provides a natural framework for synchronization, since the data flows are delimited by the handover messages themselves.

This paper presents a comprehensive work aimed at defining possible solutions and a general analysis method for network-level handover protocols in integrated networks. Within this framework some detailed protocols for the control of handover procedures performed by using in-band signaling are presented and analyzed, extending and completing the ideas proposed in [23], [24], [25]. Also, results for concurrent handovers at the same access point are derived. In [23] the idea of in-band signaling for handover management was first sketched for a simple handover scheme similar to those of 2nd generation cellular networks. The work in [24] presented a detailed simulation analysis of buffer requirements for a single handover procedure with variable network parameters for the same handover scheme considered in [23]. In [25] the need for different network handover schemes in a mobile, integrated network, and an early version of the handover classification adopted here, were illustrated.

We claim that the in-band signaling approach for handover management has not been considered thoroughly in the literature; thus, the definition, validation, analysis, and implementation in a simulated environment of handover procedures based on in-band signaling is an original contribution of this work. The performance of the handover procedures is shown to be good and the complexity is comparable with that of other schemes. In addition, the paper proposes a novel, simple analytical method for performance evaluation of handover procedures. This approach is not specific for in-band signaling and represents a useful tool for the evaluation of general handover procedures.

II. THE NETWORK REFERENCE MODEL

Handover procedures and related protocols are heavily influenced by the network architecture. For instance, in GSM-like and CDMA-based cellular networks handover procedures are fairly different. The network architecture considered here implies a complete integration of mobile terminals (MTs) within the ATM network, and was described in detail in [23]. Notice that, on the one hand, the network model is purposely not very detailed to abstract the procedures from any implementation or unnecessary detail; on the other hand, the procedures were implemented in a cell level, detailed ATM network simulator (see Sec. V) ensuring that they work properly in an ATM network.

The key aspects of the considered network architecture are: i) handover procedures must be handled at the ATM level and must be independent from the underlying radio level, and ii) connection re-routing must be performed efficiently and without resource waste. The first point does not imply that radio level handover procedures are either absent or irrelevant, rather that ATM level handover procedures and rerouting operate independently of the layers underneath. For example, the radio interface can exploit a CDMA technique and macrodiversity can be used at the radio level ensuring high reliability and smooth transitions from one physical interface (antenna or Base Transceiver Station – BTS) to the next one: only when the mobile crosses the border between *domains* managed by different Base Station Controllers (BSC), an ATM level handover procedure is needed, just like in GSM networks where MSC (Mobile Switching Center) manages the handover procedure only when MT crosses the boundary between two BSCs areas.

The protocol architecture must provide for a wireless control and mobility control layer, but no other requirements are imposed. The handover management exploits the *incremental VC re-establishment* approach: The VC route is dynamically recomputed during the handover, breaking the VC in a suitable node and re-establishing its terminal portion starting from this node. BSCs are traffic concentrators and do not have routing capabilities; the nodes to which BSCs are connected are termed End-User Mobility Supporting ATM Switch at the Edge (EMAS-E) and the node that performs the connection re-routing is named Cross-Over Switch (COS), adopting the ATM Forum terminology[2]. The assumption that BSCs do not have routing capabilities is not restrictive, since a BSC with routing capabilities just concentrates the functionalities of BSC and EMAS-E.

As discussed in [23], two handover types can be envisaged, involving a different number of network entities: in the first case, both the *source* BSC (BSC_1) and the *destination* BSC (BSC_2) are connected to the same EMAS-E, originating *local*[3] handovers; in the second case, the two BSCs (BSC_2 and BSC_3) are connected to different EMAS-Es, originating *global*[4] handovers. The latter constitute a crucial point toward the objective of an *integrated mobile network*, where the user can freely roam through the network, moving from one subnet and operator to another. As a general rule in protocol definition, we assume that the switches of an integrated network incorporating mobility services should not be burdened with too much overhead for mobility management: BSC should undertake mobility management tasks as far as possible.

Without the pretense of being exhaustive in the discussion of the literature, we only compare our approach with the draft standard of the ATM Forum [8].

The ATM Forum considers a *mobile initiated* backward handover, while here we present a *network initiated* backward handover. The difference is marginal; we defined the *mobile ini-*

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[2] Although we often adopt ATM Forum terminology for the sake of clarity, we do not claim that the work presented here is compliant with ATM Forum specifications.

[3] *Intra-EMAS-E handover* in ATM Forum jargon.

[4] *Inter-EMAS-E handover* in ATM Forum jargon.

tiated backward handover in [28] and the interested reader can refer to that document. ATM Forum procedures are described by assuming that EMAS-E and BSC are embedded in the same device.

Apart from the signaling technique, the first striking difference is that ATM Forum procedures are not seamless (according to the meaning of the term adopted in this paper). This difference prevents a possible comparison based on buffering requirements, and it is also responsible of a greater complexity in the forward handover presented here because the retrieval of cells from the old EMAS-E requires additional operations.

A second major difference lies in the role that the COS plays in the procedures. We assume that EMAS-Es are not connected directly through a signaling channel, and the COS has the role of checking the availability of resources at the new EMAS-E. The ATM Forum procedures, instead, assume that EMAS-Es are directly connected through a signaling channel. Which solution is superior is difficult to state in general. For instance, if we consider the handover latency, the relative speed of the two procedures depends on the relative topological position of EMAS-Es and COS.

A further difference lies in the time instant the COS performs the connection switch. We assume that the switch of each VC (uplink and downlink) is independent and is not synchronized with the MT disassociation from the old access point and association with the new one. The ATM Forum, instead, forces all the VCs of the connection to be switched at the same time, the time instant being synchronized between the disassociation and the new association. Once again it is hard to state which solution is superior.

A. In-band Signaling for Handover Procedures

In-band signaling is implemented by means of dedicated Resource Management (RM) cells, similar to those used in the ABR (Available Bit Rate) and ABT (ATM Block Transfer) ATM transfer capabilities [29]. These cells, termed Mobility Enhancement Signaling (MES) cells, are inserted in the data flow of the connection when needed, and provide the exchange of information among the nodes along the connection path. A possible format of MES cells, compliant with standard RM cells, is reported in [23], [28].

The rationale behind the use of in-band signaling for handover procedures in Wireless ATM is threefold.

First of all, MES cells transparently cross the ATM switches of the fixed network that are not upgraded to handle dynamic VC re-establishment. This allows a gradual introduction in the fixed network of ATM switches capable of interpreting MES cells and thus participating in the VC re-establishment procedure.

Second, the signaling flow related to handover procedures is limited to a small number of network entities, and it is strictly related to the information flow. All entities involved in the handover must interpret the signaling messages, and do it in real-time while managing the information flow; a situation fairly different from Call Management or Intelligent Network Signaling in PSTN and ISDN. Since the handover procedure operations must be synchronized between MT, BSCs and nodes in order to grant a seamless handover, the use of RM cells provides a natural framework for protocol synchronization without the need for global network or connection synchronization. Moreover, in-band signaling ensures that all and only the entities involved in the handover receive the signaling messages, a condition that is hard to reproduce with common channel signaling.

Third, given the poor propagation characteristics, the bandwidth allocated over the radio channel should be somewhat larger than the Sustainable Cell Rate (SCR) of the VC, in order to leave capacity for retransmissions. In-band signaling and retransmissions can be statistically multiplexed on the extra bandwidth, thus sparing some resources. The wired part of the VC must be suitably dimensioned by the network to avoid mismatches between the air interface and other interfaces within the network. This is however a minor problem, even in the case of synchronous CBR flows: RM cells are not considered by the AAL (ATM Adaptation Layer) that re-constructs timing information.

Finally, consider that VPI/VCI identifiers are local to interfaces, so that a non marginal amount of information must be transferred between network entities to identify the VCs that must be re-routed. Clearly, in-band signaling simplifies this problem.

B. Interaction with Other Mobility Related Procedures

Although this paper discusses only handovers via in-band signaling, we do not claim that in-band signaling is a panacea for wireless ATM, nor we disregard the presence of other, equally important mobility related procedures, like registration, authentication, localization and paging, or call management procedures, like connection setup and release.

First of all, some functions, like registration and paging, are performed without an active user channel, hence in-band signaling can not be used. We kept the network architecture as general as possible from the mobility point of view, without specifying, for example, where the mobility data-bases are located, or which entities manage mobility related information at the application level. This is done on purpose to show that handovers based on in-band signaling can be applied in a very general scenario. Notice that registration, authentication and similar procedures, are logically separated from handover management and the update of location data-bases is best done with common channel signaling. For instance, the new EMAS-E can do the update as soon as the handover is successfully completed.

III. PROTOCOLS FOR TWO HANDOVER PROCEDURES

In the following, two hard handover protocols based on in-band signaling are presented: A backward handover and a forward handover. All other protocols for the admissible handover procedures identified in Fig. 1 can be found in [28]; they are not reported here for the sake of brevity.

A backward handover protocol is the standard procedure performed by MT when any “normal” reason causes the mobile user to change BSC. A forward handover protocol is run when a sudden radio link failure occurs and MT attempts to recover the connection with another BSC. For the former, we consider a network-initiated procedure; while for the latter we assume that the handover is started by MT.

In the presented protocols, in order to guarantee loss-free and in-sequence cell delivery we propose to temporarily buffer data

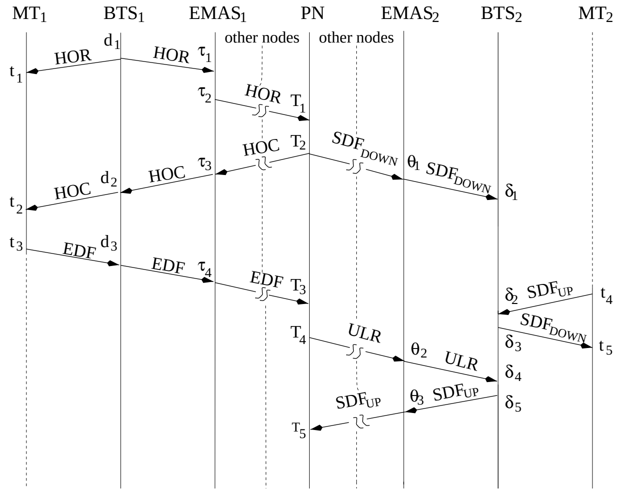

Fig. 2. Message flow of a hard backward network-initiated handover.

at the BSCs. This approach has the significant advantage to require the least amount of changes at the ATM nodes, and thus reduce the cost of the mobility features implementation. The same protocols can be re-designed with little modification for buffering at COS or EMAS-Es. Some data must be stored at the MT anyway, but this is a minor concern.

In the handover description, the source and destination BSCs are denoted by BSC_1 and BSC_2, respectively, while MT is denoted by MT_1 while it is connected to BSC_1 and by MT_2 when it is connected to BSC_2. Since in local handovers only one EMAS-E is involved in the procedure, and the same EMAS-E behaves as COS, all the protocols will be illustrated only for the more general case of global handovers.

COS discovery is not discussed here but can be performed by using any of the algorithms described in the literature [17], [30], [31], [32]; moreover, COS discovery can be performed off-line and the results stored in a table, so that the time for COS discovery during the handover is minimized.

The described protocols assume that the MT is already registered with the network; in fact, as discussed in Sec. II-B, this task can not be performed with in-band signaling. For the sake of simplicity, we also do not consider call management procedures that can be handled via standard (or enhanced) ATM signaling.

A. Backward, Network-Initiated Handover

The protocol message flow diagram of a backward network-initiated handover is illustrated in Fig. 2. Let us consider a mobile terminal that moves from the domain controlled by BSC_1 to the domain controlled by BSC_2. When BSC_1 decides that MT has to perform a handover, it sends a HOR (HandOver Request) message on both the downstream and upstream connections.

Upon receiving the HOR message, $\mathrm{EMAS\text{-}E}_1$ identifies the COS (time interval $[\tau_1, \tau_2]$), and forwards the handover request to it. The COS verifies whether a new connection path can be opened through BSC_2. In the successful case, the COS sends the HOC (HandOver Confirm) message to MT through BSC_1; otherwise, the handover request is refused, and the COS sends a HOD (HandOver Denied) message.

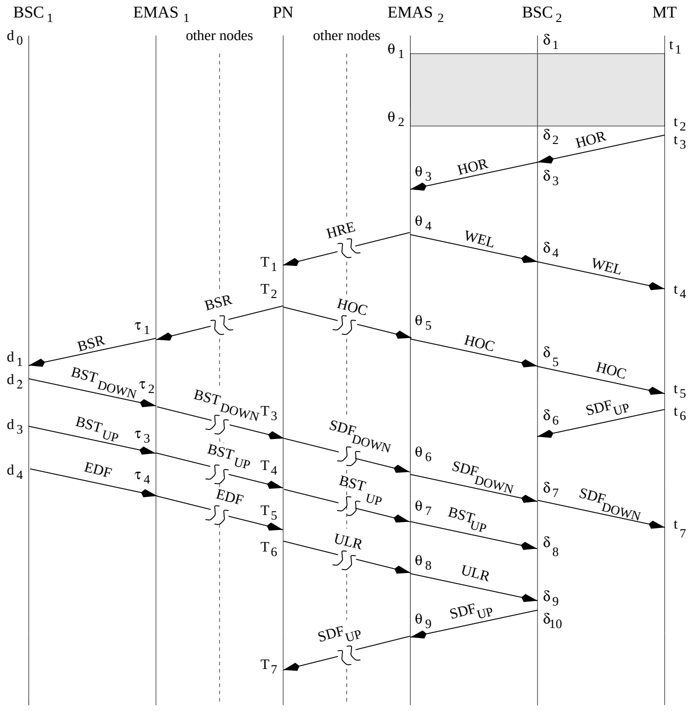

Fig. 3. Message flow of a hard forward mobile-initiated handover.

As soon as the HOC MES cell is transmitted, the COS updates the downstream routing table, and starts sending the downstream data flow, preceded by the message $\mathrm{SDF}_{\mathrm{DOWN}}$ (Start Data Flow on the DOWNstream connection), toward BSC_2. These cells are stored in the downstream handover buffer at BSC_2, until they can be delivered to MT over the radio link (time interval $[\delta_1, \delta_3]$). The transmission of HOC and $\mathrm{SDF}_{\mathrm{DOWN}}$ messages can be done almost at the same time and they might be merged in the same MES cell, because the transmission of HOC can be delayed until the downstream routing tables are ready to be updated.

While waiting for the HOC message, MT continues sending (receiving) data cells over the original upstream (downstream) connection. After receiving the HOC message, MT ends its upstream transmission through BSC_1 by sending the EDF (End Data Flow) message, and disconnects from BSC_1. The upstream transmission is resumed at time instant t_4 when the radio link is established between MT and BSC_2; in the meanwhile, MT buffers the generated traffic in its transmission buffer (time interval $[t_3, t_4]$). Once the EDF message reaches the COS, the upstream routing table at the switch is updated (time interval $[T_3, T_4]$), and the ULR (Upstream Link Ready) message is transmitted to BSC_2, to notify that the upstream connection path has been re-routed.

After the radio link is recovered, MT sends the $\mathrm{SDF}_{\mathrm{UP}}$ (Start Data Flow on the UPstream connection) message and begins to transmit the upstream data cells to BSC_2, whereas BSC_2 starts sending cells to MT on the downstream radio link. Cells arriving at BSC_2 from MT are stored in the *upstream handover buffer* until ULR reaches BSC_2 (time interval $[\delta_2, \delta_5]$). The handover protocol ends when the $\mathrm{SDF}_{\mathrm{UP}}$ message is forwarded by BSC_2 to the COS on the new wired connection path.

The handover could be terminated in a slightly different way, buffering upstream cells at MT only and resuming transmission on the uplink when the ULR message (forwarded also to MT) arrives. This is perfectly viable and a protocol providing for both solutions can be easily envisaged. We choose the buffering at the BSC because it slightly reduces the handover latency, and we deem that buffering *also* upstream cells besides downstream ones is not a major burden for the BSC.

B. Forward, Mobile-Initiated Handover

The need for this handover configuration stems from the possibility of sudden failure of the radio connection between MT and BSC_1, a possibility that with large bandwidth and high frequency channels is much more realistic than in narrowband cellular networks. As illustrated in Fig. 3, the MT connection to BSC_1 is not considered at all; it has no influence on the handover procedure since we assume that the connection is resumed through a different BSC. MT tries to re-connect to the network, and a BSC different from the previous one is contacted at instant t_1. For the sake of clarity, in the performance analysis we will assume that the connection was interrupted at time d_0.

Since no connection is active between MT and the network, the use of in-band signaling to start the handover procedure must be preceded by a signaling phase (not considered in this paper) necessary for MT registration. This phase can be performed with any signaling procedures available for such tasks as discussed in Sec. II-B.

The time needed to perform these tasks is highlighted by the shaded area bounded by $t_1, t_2, \theta_1, \theta_2$ in Fig. 3; in this time interval, MT has to notify BSC_2 that the connection request does not refer to a new connection, but it is for handover purposes and that it was previously connected to BSC_1.

¿From instant t_3 on, in-band signaling can be resumed, and MT sends the HOR message to the destination BSC it just connected to. As an acknowledgment of the resumed operation, EMAS-E_2 sends the WEL (WELcome) message to MT, while it sends the HRE (Handover REsume) message to the COS, requiring the handover procedure to be performed. The time interval $[\theta_3, \theta_4]$ is used to identify the COS. Since in this case BSC_2 does not know the path of the connection before the connection with MT is resumed, this task may require a non-negligible amount of time.

If the COS can not be found in time, or if the new connection can not be established, the network (either EMAS-E_2 or the COS) transmits a HOD message; otherwise, it acknowledges the requested handover by sending the HOC message. Afterwards, MT_2 starts transmitting the upstream information to BSC_2, that buffers the data until the upstream connection through the network is ready.

During the time interval $[T_2, T_5]$, COS contacts BSC_1 and recovers the downstream and upstream data buffered at BSC_1 after the radio link failure. When BSC_1 starts emptying the downstream buffer related to the MT that is performing the handover, it sends the BST_{DOWN} (DOWNstream Buffer STatus) message to the COS. This information coming from BSC_1 is forwarded by COS to MT. The BST_{UP} (UPstream Buffer STatus) message ends the data flow to be delivered to MT, and starts the upstream data flow that COS has to forward to the remote terminal. We point out that since BSC_1 can keep forwarding cells to the COS after the disconnection of MT, usually the upstream buffer at BSC_1 is empty: in this case the BST_{UP} and the EDF messages coincide and can be sent within the same MES cell. The three messages BST_{DOWN}, BST_{UP} and EDF, are kept logically separate in the protocol for the sake of completeness and generality, although the upstream buffer should always be empty. It is an implementation choice whether to merge some of these messages or not; notice however that in some situation the availability of an upstream buffer can be useful, if not necessary. For instance, if the upstream and downstream radio channels are obtained by FDD (Frequency Division Duplex), it may happen that the downstream channel is disrupted, while the upstream one is good and MT can keep transmitting cells while trying to contact a new BST.

After the flow from BSC_1 ends, COS updates the upstream routing tables and sends the ULR message to BSC_2. By sending the SDF_{UP} message to the COS, BSC_2 completes the handover procedure, and starts emptying the upstream handover buffer.

With reference to Fig. 3, starting from time T_2, the cells coming from the connection remote endpoint should be forwarded to BSC_2, as well as the cells retrieved from BSC_1. Since our choice is to buffer only at BSC_2, not at the COS, an *auxiliary* VC must be used to transfer cells from BSC_1 to BSC_2.

In forward handover procedures, the simple buffering scheme provided by BSC_2 in backward handovers is not sufficient to ensure a lossless handover with in-sequence cell delivery. In order to deliver the downstream cells with the proper ordering, those retrieved from BSC_1 must be stored in a queue logically different from the downstream buffer used to collect the data flow from the connection remote endpoint. Forwarding the BST_{UP} message to BSC_2 indicates that all cells have been retrieved from BSC_1, and the two downstream buffers can be concatenated to transmit all cells in the proper order to MT.

IV. PROTOCOL VERIFICATION

The protocols correctness is verified by using a formal description based on Petri nets (PNs). Examples of protocol verification with Petri Nets can be found for instance in [33].

Fig. 4 reports a PN description of the handover protocol illustrated in Fig. 2. For the sake of brevity, the PN description of the other protocol is omitted, however its PN validation yielded the same positive result as for the protocol we discuss. The PN description of the protocol and the analysis of the PN properties are based on GreatSPN [34], a software tool for the development and the analysis of PN models.

The name of places and transitions in the PN description of the handover protocol should be, in general, self explaining, based on the protocol description provided in Sec. III-A. Here, we just briefly comment on some specific aspects of the PN protocol representation that might not be standard.

In Fig. 4 the PN is depicted with the marking (distribution of tokens in places) relative to the phase between two handovers. The only enabled transition in this marking is the one that corresponds to the beginning of a new handover in the PN. The fact that no temporal specifications are included in the PN model implies that the protocol description is valid for all possible orderings of events, thus for all combinations of delays (deterministic

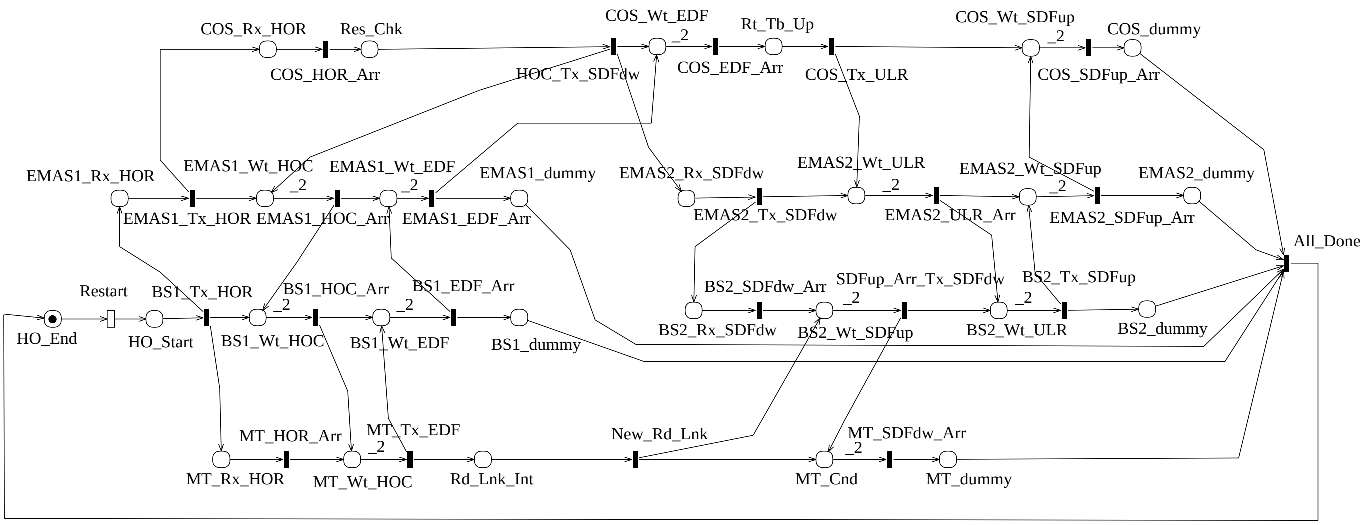

Fig. 4. Petri Net description of the hard, backward, network initiated handover.

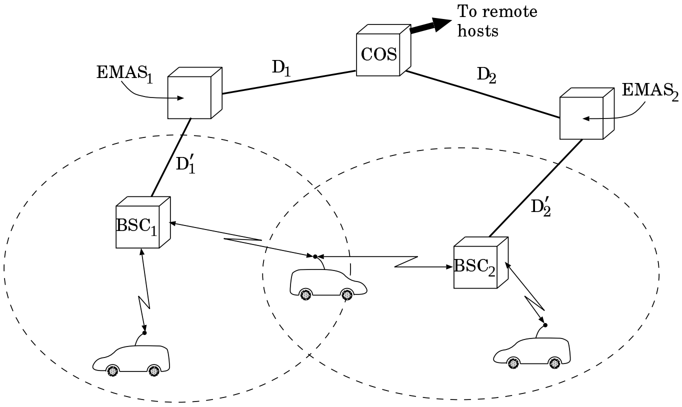

Fig. 5. Reference network configuration adopted for performance evaluation.

or stochastic) between different protocol actions.

The results of the GreatSPN analysis of the PN model show that the protocol has 78 possible states (markings of the PN), none of which is a deadlock. Similarly, the protocol can be observed to always terminate in a finite number of actions, and always return to the initial state after a finite and limited number of message exchanges.

All places of the PN are covered by P-invariants, and all transitions in the PN are covered by only one T-invariant. This implies that the properties that are observed on the PN reachability graph can also be proven with the linear algebraic techniques typical of PN theory (see for instance [35], [36] for the proof of properties of PN models with structural techniques).

In summary, we can conclude that the handover protocol is correctly defined.

V. CONFIGURATION FOR PERFORMANCE EVALUATION

Fig. 5 shows the network setup that we consider for performance evaluation of handover procedures, both through the analytical method presented in Sec. VI and via simulation.

We consider global network handovers, with two BSCs connected to their corresponding EMAS-Es, and one COS connecting the two EMAS-Es. The times required for COS searching, routing procedures, and similar tasks are described stochastically. We assume homogeneous calls consisting of a single VBR (Variable Bit Rate) connection: the extension to non homogeneous, multimedia (multiple VCs) calls is cumbersome but straightforward, since it just consists in keeping track of the multiple VCs with their different loads and (if per VC queuing is provided) of the multiple buffers during handover.

Without any loss of generality, simulations and analysis are carried out under the assumptions that a TDMA radio interface is used and that the VC rate at the BSCs is controlled by a GCRA (Generic Cell Rate Algorithm) shaping device implemented as VSA (Virtual Scheduling Algorithm) [29], while the auxiliary VC used in forward handovers is a DBR (Deterministic Bit Rate) VC, with rate AVCR (Auxiliary Virtual Circuit Rate).

Simulation results were obtained by implementing the proposed handover protocols in CLASS[5] [37] and observing several thousands handover procedures. We point out that the cell-level detail provided by CLASS allows for an effective implementation of the in-band signaling procedure with the explicit transmission of signaling messages, so that the risk of over-simplified simulation modeling is avoided. Table I reports the definition of the parameters used in the analysis.

Given the kind of analysis that we perform, either on a single handover procedure or based on the number of handover performed per BSC, the mobility model and the channel radio propagation characteristics have no influence on the results.

[5] CLASS is a cell-level simulator of ATM networks developed at the Electronics Department of Politecnico di Torino in cooperation with CSELT (the research center of Telecom Italia) and the Technical University of Budapest; CLASS stands for Cell Level ATM network Services Simulator; it is entirely written in C language and portable on most computing platforms. Information on CLASS is available at the URL `http://www1.tlc.polito.it/class.html`, and details about the simulations can be obtained via e-mail from the authors.

TABLE I

PARAMETERS USED IN THE HANDOVER ANALYSIS.

PCR, SCR	Peak and Sustainable Cell Rates of VBR connections; the former is set equal to the radio link capacity.
AVCR	Cell rate of the auxiliary DBR VC.
L_o	Average offered load per connection.
T_p	Cell propagation delay over the radio link.
T_{REG}	Registration phase duration ($[\theta_2 - \theta_1]$ in Fig. 3).
T_{UPD}	Time required to update the routing tables of the ATM switch and build the incremental path of the ongoing connection.
T_{COS}	Time required to identify the COS ($[\theta_4 - \theta_3]$ in Fig. 3).
τ_{SCR}, τ_{PCR}, τ_{AVCR}	Time interval between two consecutive cell transmissions at PCR, SCR, and AVCR rate, respectively.
γ_{COS}, γ_{BSC}, γ_{MT}	MES cell processing delay at the COS, at BSC, and at MT.
ξ_{MES}, ξ_{mes}	Time between a MES cell generation (arrival) at the MT (BSC) and its transmission over the radio link; it assumes values uniformly distributed over $[0, \tau_{\text{SCR}}]$.
D_i', D_i	Cell propagation delay between BSC$_i$ and EMAS-E$_i$, and EMAS-E$_i$ and the COS, respectively.

VI. ANALYSIS OF TIME DELAY AND BUFFER REQUIREMENTS

In this section we present an analytical method for the evaluation of the maximum additional delay introduced by handover procedures (a key performance parameter for real time services), as well as buffer requirements for a single handover procedure at the BSCs. As shown in the following, the two parameters are tightly coupled. Hints on the possibility of analytically compute some performance parameters of handover procedures were already given in [24], and some results appeared in [38] that make use of a similar methodology. The latter, however, allow only for a worst case analysis of delays, that in most cases are far from real values; moreover, no evidence is given (e.g., measures, simulation experiments) that the derived worst case value is consistent with any implementation.

The analysis is presented for the case of the forward, mobile-initiated handover procedure defined in Sec. III-B (i.e., the most complex procedure we presented), but it is quite general and can be applied to any handover procedure, regardless of the adopted signaling technique. The only simplifying assumption we make is that the upstream buffer at BSC$_1$ is empty when MT reconnects to the network: this is a reasonable assumption and, as discussed in Sec. III-B, is confirmed by simulation results.

The rationale of the analysis is the computation, for each considered buffer, of the time interval, denoted by I, during which each buffer involved in the procedure is filled and emptied. The maximum buffer occupancy η is inferred based on the differential flow of cells entering the buffer under examination. The subscripts $_{D,U,A}$ refer to Downstream, Upstream and Auxiliary buffers, respectively; the superscript $^{(1,2)}$ refers to BSC 1 and 2, respectively. All quantities are random processes and are defined in Table I.

Referring to Fig. 3, the time instant d_0 at BSC$_1$ identifies the sudden interruption of the radio channel. From d_0 onwards the data flow transmitted by the remote user to BSC$_1$ can not be delivered to MT and cells have to be stored in the downstream buffer at BSC$_1$. Cells are buffered until the time instant d_2, when the buffer starts to empty. Thus, cells are buffered at BSC$_1$ during the time interval

$$\begin{aligned} I^{(1)}_{[d_0,d_2]} &= T_{\text{REG}} + T_p + \xi_{\text{HOR}} + D_1 + D_1' + D_2 + D_2' \\ &\quad + \gamma_{\text{BSC}} + 2\gamma_{\text{EMAS-E}} + \gamma_{\text{COS}} + T_{\text{UPD}} + T_{\text{COS}} \; . \end{aligned} \tag{1}$$

By assuming that γ_{COS}, $\gamma_{\text{EMAS-E}}$, γ_{BSC} are negligible, we obtain

$$I^{(1)}_{[d_0,d_2]} = T_{\text{REG}} + T_p + \xi_{\text{HOR}} + D_1 + D_1' + D_2 + D_2' + T_{\text{UPD}} + T_{\text{COS}} \; . \tag{2}$$

Therefore, the maximum number of cells that are buffered in the downstream buffer at BSC$_1$ is

$$\eta^{(1)}_{\text{D}} = \frac{I^{(1)}_{[d_0,d_2]} \cdot L_{\text{o}}}{424} \tag{3}$$

where 424 are the bits in one ATM cell. ¿From the time instant d_2, BSC$_1$ starts transmitting the buffered cells to BSC$_2$ at AVCR; then, the time necessary to empty the downstream buffer is

$$I^{(1)}_{[d_2,d_3]} = \eta^{(1)}_{\text{D}} \cdot \tau_{\text{AVCR}} \; . \tag{4}$$

The whole time occupancy of the downstream buffer at BSC$_1$ can be written as

$$I^{(1)}_{\text{D}} = I^{(1)}_{[d_0,d_1]} + I^{(1)}_{[d_2,d_3]} \tag{5}$$

in accordance with the assumption of negligible cell processing times.

As described in Sec. III-B, the cells from BSC$_1$ are delivered to MT by BSC$_2$ over the radio link at PCR. If AVCR $>$ PCR, cells are stored in the auxiliary downstream buffer at BSC$_2$; otherwise cells just pass through this buffer. The time needed to deliver all cells coming from BSC$_1$ to MT is

$$I^{(2)}_{\text{A}} = (\eta^{(1)}_{\text{D}} + 1)\tau_{\text{PCR}} \tag{6}$$

where one additional cell representing the SDF$_{\text{DOWN}}$ message must be added to $\eta^{(1)}_{D}$. The maximum number of cells buffered in the auxiliary downstream buffer is

$$\eta^{(2)}_{\text{A}} = \frac{\eta^{(1)}_{\text{D}} + 1}{\text{AVCR}}(\text{AVCR} - \text{PCR}) \; . \tag{7}$$

Cells coming from the remote user and sent by the COS to BSC_2 can not be transmitted to MT until the cells flow from BSC_1 ends. By taking into account the transmission of $\mathrm{BST}_{\mathrm{UP}}$, and neglecting processing times, the interval during which cells must accumulate in the downstream buffer at BSC_2 is derived as

$$\begin{aligned} I^{(2)}_{[\delta_5,\delta_8]} &= D_1 + D_1' - D_2 - D_2' + D_1 + D_1' + D_2 + D_2' \\ &\quad + 2\gamma_{\mathrm{BSC}} + 2\gamma_{\mathrm{EMAS\text{-}E}} + \gamma_{\mathrm{COS}} + I^{(2)}_{\mathrm{A}} + \tau_{\mathrm{AVCR}} \\ &= 2(D_1 + D_1') + I^{(2)}_{\mathrm{A}} + \tau_{\mathrm{AVCR}} \; . \end{aligned} \tag{8}$$

For the downstream buffer occupancy at BSC_2, we obtain

$$\eta^{(2)}_{\mathrm{D}} = \frac{I^{(2)}_{[\delta_5,\delta_8]} \cdot L_{\mathrm{o}}}{424} \; . \tag{9}$$

Since from time instant δ_8 the cells stored in the downstream buffer at BSC_2 are forwarded to MT at PCR, while the data flow from the remote user arrives at BSC_2 at rate L_{o}, the total time during which the downstream buffer is used by the MT connection is

$$I^{(2)}_{\mathrm{D}} = I^{(2)}_{[\delta_5,\delta_8]} + \frac{\eta^{(2)}_{\mathrm{D}}}{(\mathrm{PCR} - L_{\mathrm{o}})} \; . \tag{10}$$

By referring again to Fig. 3 and neglecting the processing time, the time period during which cells are stored in the upstream buffer at BSC_2 and can not be forwarded toward the COS is

$$\begin{aligned} I^{(2)}_{[\delta_6,\delta_{10}]} &= I^{(2)}_{\mathrm{A}} + D_1 + D_1' + D_2 + D_2' + T_{\mathrm{UPD}} + 2\tau_{\mathrm{AVCR}} \\ &\quad - 2T_p - \xi_{SDF_{\mathrm{UP}}} - \xi_{HOC} \; . \end{aligned} \tag{11}$$

The maximum number of cells that are buffered in the upstream buffer is computed by considering that during the time interval $[\delta_6, \delta_8]$ the buffer is filled by MT at SCR,

$$\eta^{(2)}_{\mathrm{U}} = \frac{I^{(2)}_{[\delta_6,\delta_{10}]}}{\tau_{\mathrm{SCR}} \cdot 424} \; . \tag{12}$$

After instant δ_{10}, BSC_2 starts emptying the upstream handover buffer at PCR; thus, this buffer is used by the MT connection for a total time equal to

$$I^{(2)}_{\mathrm{U}} = I^{(2)}_{[\delta_6,\delta_{10}]} + \frac{\eta^{(2)}_{\mathrm{U}}}{(\mathrm{PCR} - \mathrm{SCR})} \; . \tag{13}$$

We notice that the rate at which the upstream buffer is filled is considered equal to SCR since we claim that a great amount of cells are stored in the MT transmission buffer due to the radio channel interruption (we are considering hard handovers). Finally, under the assumption that the MES cell processing time is negligible, we derive the delay due to the whole handover procedure as

$$\begin{aligned} \Delta_{\mathrm{HO}} &= T_{\mathrm{REG}} + \xi_{\mathrm{HOR}} + T_p + T_{\mathrm{COS}} + 2T_{\mathrm{UPD}} + 2(D_2 + D_2') + \\ &\quad I^{(1)}_{[d_3,d_4]} + 2\tau_{\mathrm{AVCR}} + 3(D_1 + D_1') \; . \end{aligned} \tag{14}$$

VII. NUMERICAL RESULTS

We present here some selected results, highlighting the main characteristics of the handover procedures defined in Sec. III. The network scenario is the one defined in Sec. V. First, in Sec. VII-A, results obtained through the analysis sketched in Sec. VI are discussed and compared with those obtained by simulation; then, in Sec. VII-B, additional insight is provided by comparing the buffering requirements of the two different procedures in the presence of concurrent handovers. These results can not be obtained analytically because concurrent handovers introduce complex correlations in buffer dynamics.

Eq. (14) clearly states that the overall delay introduced by the handover depends only on the sum of transmission delays between the BSCs and the COS; (2)–(12), show that also the buffer occupancy depends on the sum of transmission delays only, not on their difference. Thus, we present results only for the special case $D_1 = D_2$ (from now on denoted by $D_{1,2}$) and $D_1' = D_2'$[6].

Unless otherwise stated, the values of the parameters used to obtain the numerical results presented in this section are the following: PCR=2.0 Mbit/s, SCR=1.9 Mbit/s, L_{o}=1.8 Mbit/s, D_1'=D_2'=0.25 ms, T_p=8.5 μs (this value corresponds to roughly 2.4 km radius, probably too large for a micro-cellular environment; however, when smaller delays are considered, performance improves); T_{REG} is a uniform random variable with support $[0.2, 0.8]$ ms (thus with mean value 0.5 ms), and T_{COS} is uniformly distributed with mean value equal to $5.5D_1$ ms, the support being $[D_1, 10D_1]$ ms. T_{UPD} is assumed to be exponentially distributed over the range of values [2,10] ms, with average equal to 4 ms[7]; whereas AVCR and $D_{1,2}$ are taken as variable parameters.

A. Analytical Results

Eq.s (3), (7), (9) and (12) give a stochastic description of the buffer needed to guarantee a lossless handover procedure, while (14) describes the overall duration of the handover itself. If the handover must not be perceived by the user, regardless the type of service the user is receiving from the network, its duration must be kept within a few tens of milliseconds. One interesting fact is that both buffer occupancy and handover duration grow linearly with the propagation delay between BSCs and the COS: Handovers can be safely handled even if the re-routing point lies hundreds of kilometers away from the BSCs.

Let us now concentrate on the handover duration. Retracing the analysis of Sec. VI on the backward, network-initiated protocol (see Sec. III-A) yields

$$\begin{aligned} \Delta^b_{\mathrm{HO}} &= \xi_{\mathrm{HOR}} + \xi_{\mathrm{HOC}} + \xi_{\mathrm{EDF}} + 3T_{\mathrm{p}} + 2T_{\mathrm{UPD}} \\ &\quad + 3(D_1 + D_1') + 2(D_2 + D_2') \end{aligned} \tag{15}$$

where the superscript ^{b} is to differentiate it from the delay expressed by (14) that refers to the forward handover. In order to compare the two procedures the Probability Density Function (PDF) of Δ_{HO} and Δ^b_{HO} must be computed; we obtained them by numerical convolution starting from the PDFs of the terms on the right hand side of (14) and (15). A close look to these two

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[6] The analysis carried out on the backward, network-initiated procedure (not reported here for the sake of brevity) showed that the upstream buffer occupancy is still a function of the sum of the propagation delays; while, the downstream buffer occupancy is less critical and depends on the difference $(D_1 + D_1') - (D_2 + D_2')$.

[7] We took these values from measures reported in [39].

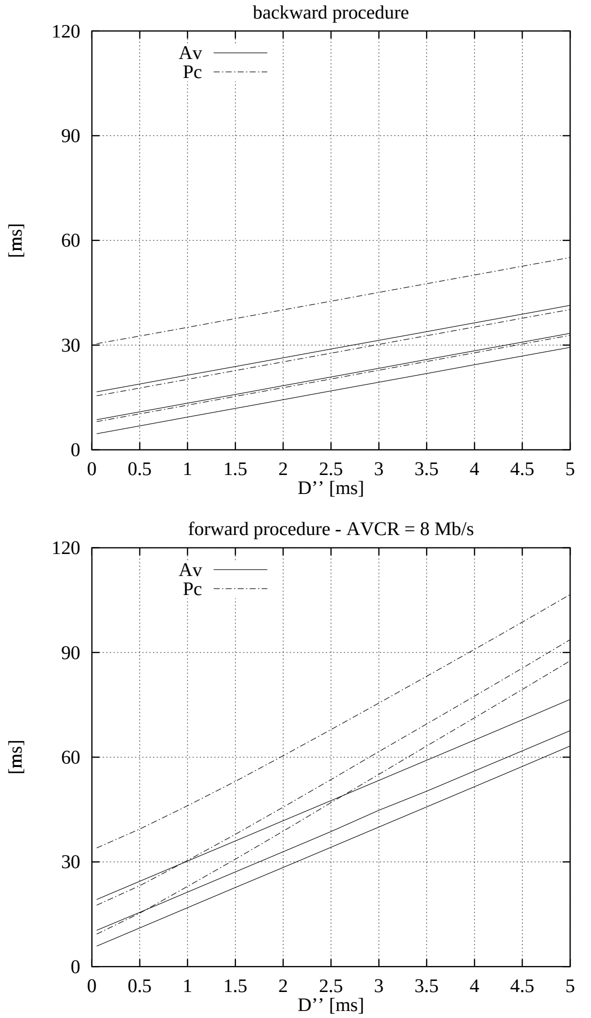

Fig. 6. Comparison of the handover duration for the backward and forward procedures (AVCR=8 Mbit/s), for increasing values of T_{UPD}: Average (Av) and $^{\underline{o}}95_{\Delta}$ (Pc).

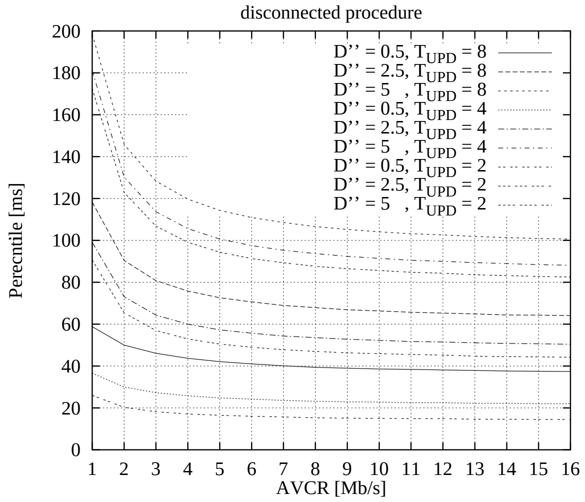

Fig. 7. Forward handover duration as a function of AVCR for different values of D" and T_{UPD}.

equations shows that the average, as well as any constant percentile value, are linear functions of $D" = D_1 + D_1' = D_2 + D_2'$,

$$^{\underline{o}}N_{\Delta} = \alpha D" + K$$

where $^{\underline{o}}N_{\Delta}$ is the N-th percentile of the delay distribution, $^{\underline{o}}50_{\Delta}$ being the mean value. For the backward handover we have $\alpha = 5$, while for the forward handover the value of α depends on AVCR.

Fig. 6 reports some samples of the average value of Δ_{HO} and Δ^{b}_{HO} as well as their 95-th percentiles as functions of $D"$. Plots report the results of the analysis when T_{UPD} is a shifted, truncated exponential distribution with minimum and maximum values equal to 0.5 and 2.5 times the mean value, respectively. The forward procedure is studied for AVCR=8 Mbit/s. The average values considered for T_{UPD} are 2, 4, and 8 ms; the curves with higher delay are clearly those with higher T_{UPD}.

Fig. 7 shows the behavior of the forward handover duration ($^{\underline{o}}95_{\Delta}$ only) as a function of the auxiliary link rate AVCR. The assumptions used to derive these results are the same as before. Different curves families (indicated by using different lines) refer to different delays $D"$, while different curves within the same family refer to different values of T_{UPD}, again with higher delays corresponding to higher T_{UPD} values. The plots show that the optimal choice for AVCR is 3–4 times the connection PCR; a further bandwidth increase on the auxiliary VC results only in a marginal reduction of the handover duration. Similar results can be obtained for any delay interval or buffer occupancy value; however, we deem that the overall duration gives enough insight into the protocol behavior.

In order to gain confidence in the accuracy of the analytical results, we compare some values with simulation results. It was not possible to compare the whole set of curves with similar ones obtained by simulation since simulations are quite long. Even assuming very high handover rates resulting in several handovers per second per connection[8], collecting results on just a few thousand handovers require the simulation of several minutes of network operations, with the transfer of hundreds of millions of cells.

Tables II–III report the values obtained with both analysis and simulation for several performance figures in the case of forward handover: T_{UPD} assumes the default distribution and $D_{1,2}$ varies. Average values are compared for all variables; and in the case of the handover duration also the percentiles are presented.

The agreement of the analysis and simulation results is remarkable, and in any case analytical results are well within the simulation confidence intervals, that, given the limited number of samples available, are no better than ±10% with 90% confidence level. The same satisfactory agreement was found for the simpler backward handover and for cells stored in the downstream buffers.

B. *Additional Simulation Results*

Simulation studies are also carried out to assess, with quantitative performance results, the feasibility of the proposed han-

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[8] We used a very large handover rate in order to reduce the simulation time. This is equivalent, though simpler, to disregard what happens between successive handovers. Notice that this is also a proof of robustness for the handover procedure, that can easily scale to very high handover rates without affecting too much the connection quality of service.

TABLE II

AVERAGE VALUE OF THE MAXIMUM NUMBER OF CELLS STORED IN THE UPSTREAM BUFFER AT BSC_2 FOR AVCR=2, 4, 8, 16 MBIT/S.

$D_{1,2}$ [ms]	AVCR=2 Mbit/s		AVCR=4 Mbit/s	
	$\eta_U^{(2)}$		$\eta_U^{(2)}$	
	analys.	simul.	analys.	simul.
0.5	61	60	40	41
5	236	226	139	144
50	2000	2057	1205	1156

	AVCR=8 Mbit/s		AVCR=16 Mbit/s	
	$\eta_U^{(2)}$		$\eta_U^{(2)}$	
	analys.	simul.	analys.	simul.
0.5	29	23	23	18
5	92	100	67	79
50	724	667	484	442

TABLE III

MEAN VALUE AND 95-TH PERCENTILE OF THE TIME DELAY DUE TO THE FORWARD HANDOVER PROCEDURE FOR AVCR=2, 4, 8, 16 MBIT/S.

AVCR=2 Mbit/s

$D_{1,2}$ [ms]	Δ_{HO} [ms]		º95$_\Delta$ [ms]	
	analys.	simul.	analys.	simul.
0.5	24.4	24.6	31.7	36.2
5	104.3	97.1	132	140
50	912.7	877.2	1171	1271.6

AVCR=4 Mbit/s

$D_{1,2}$ [ms]	Δ_{HO} [ms]		º95$_\Delta$ [ms]	
	analys.	simul.	analys.	simul.
0.5	19.6	19.9	27.2	30.7
5	83.0	79.9	107.1	110.9
50	722.8	690.8	938.5	1000.8

AVCR=8 Mbit/s

$D_{1,2}$ [ms]	Δ_{HO} [ms]		º95$_\Delta$ [ms]	
	analys.	simul.	analys.	simul.
0.5	17.7	17.9	24.6	26.6
5	72.3	68.8	95	95.4
50	627.9	604.5	830.2	862.3

AVCR=16 Mbit/s

$D_{1,2}$ [ms]	Δ_{HO}		º95$_\Delta$ [ms]	
	analys.	simul.	analys.	simul.
0.5	16.6	17.1	23.3	25.2
5	67.0	64.8	89.4	89.5
50	580.4	565.1	781.6	797.7

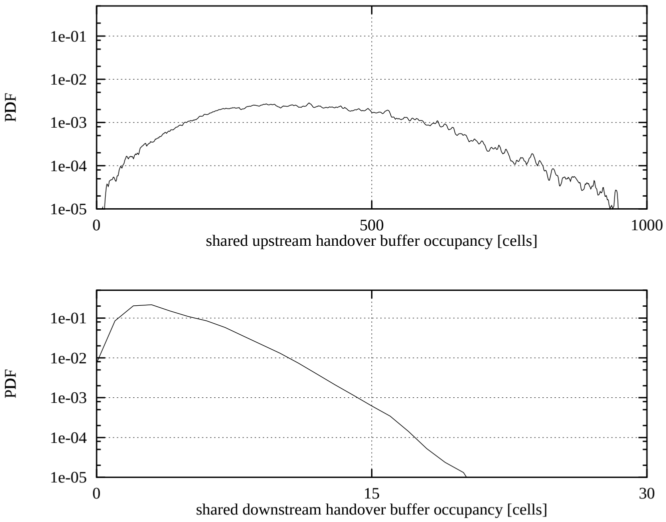

Fig. 8. Backward, BSC-initiated Handover: PDF of upstream and downstream buffer occupancy at BS_2.

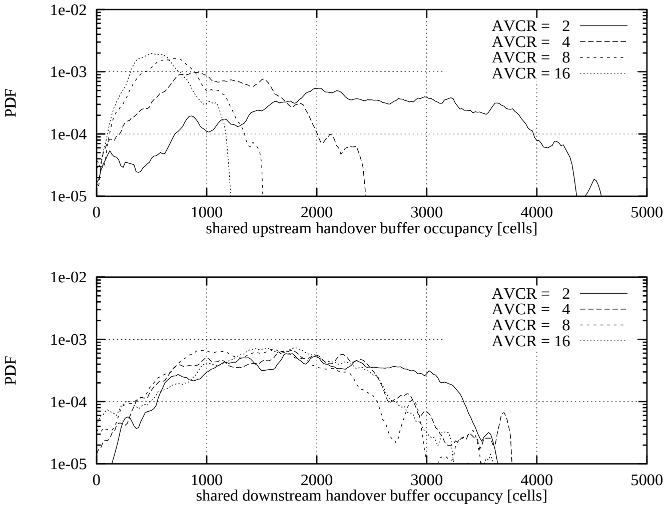

Fig. 9. Forward, MT-initiated Handover: PDF of upstream and downstream buffer occupancy at BS_2.

dover protocols.

While the analysis gives detailed insight into the behavior of a single handover procedure, it fails to describe the buffer requirements of several parallel handovers. Our reference scenario allows only for handovers that, given the destination BSC, have all the same source BSC, but the results are still valid also if source BSCs are different. We choose to fix the maximum allowed number of handovers per destination BSC to 8. Simulations were run for a period of time covering several thousands handovers, thus giving good confidence in the results. The network load and handover rate are tuned to give a handover blocking probability equal to 2%: A fairly high value, meaning that destinations BSCs are under stress. All results show the buffer occupancy resulting from all the active handovers at any given time, thus representing the buffer requirements at BSC to handle up to 8 handovers at the same time.

Fig.s 8 and 9 show the PDFs of the upstream and downstream

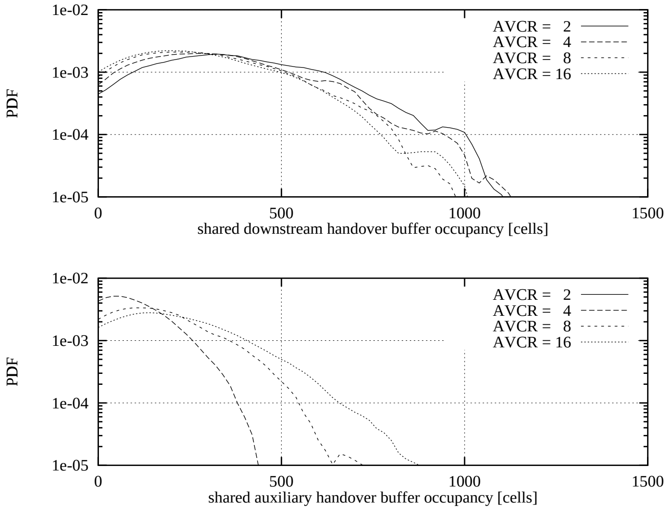

Fig. 10. Forward, MT-initiated Handover: PDF of downstream buffer occupancy at BS_1 and auxiliary buffer occupancy at BS_2.

handover buffers occupancy at BS_2 in the case of backward and forward handovers, respectively. Results are derived for $D_{1,2}$=5 ms, and, in the case of forward handover, for several values of AVCR. As expected, the buffer occupancy is less critical in backward than in forward handovers; for the upstream buffer the difference is striking. Indeed, in forward procedures the channel disruption time is much longer, as reflected by the downstream buffer occupancy. However, the upstream buffer occupancy is three orders of magnitude larger: A proportion that is not due to different overall durations, but to the fact that the cannel transition was not prepared in advance. We notice that using a large capacity auxiliary VC (AVCR=16 Mbit/s) helps in keeping the upstream buffer occupancy low.

Fig. 10 presents similar curves for the two buffers that are present in forward procedures only. The downstream buffer at BS_1 and the auxiliary downstream buffer at BS_2. As expected, the former is practically independent from AVCR because its maximum occupancy is reached before the auxiliary VC starts draining cells from it, while the latter is empty for AVCR=2 Mbit/s but its occupancy grows as AVCR increases. Looking at the presented results, we can conclude that an auxiliary VC 4–5 times faster than the connection PCR yields the best tradeoff between handover performance and network resources usage. Indeed, the larger the bandwidth of the auxiliary VC the shorter its life; therefore, a larger bandwidth auxiliary VC is not a real waste of resources.

VIII. CONCLUSIONS

This paper presented an in-band signaling solution for handover management in integrated networks supporting mobile services. The network core infrastructure is supposed to be ATM, and the ATM VC is extended all the way to the mobile terminal, thus making the scenario an integrated Wireless ATM network.

In-band signaling is a novel signaling technique for handover procedures first proposed by the authors, and its advantages and disadvantages for the support of ATM network handovers was briefly discussed, pointing out that it must be integrated with other procedures to support mobility related functionalities when user connections are not active.

Two handover procedures were presented, one for a network initiated backward handover, the other one for a mobile initiated forward handover. The handover protocols were also compared with the ATM Forum Draft Standard and with other proposals appeared in the literature, showing that, besides the in-band signaling approach, the procedures are original and innovative.

Performance of the handover procedures was evaluated both in terms of channel disruption time, resulting in additional delay added to the VC cells, and in terms of buffering requirements posed to the network to ensure a lossless procedure with in-sequence cell delivery. This feature is extremely important for data and multimedia services, but so far it was little considered.

Performance evaluation was carried out both analytically, with a simple method introduced in the paper, and through detailed discrete-event simulations. Simulations had the purpose of i) validating the approximate analysis, and ii) showing the viability of in-band signaling with an implementation of the protocols.

The contribution of this paper lies in two separate areas. First of all it presented, discussed and showed the feasibility and good performance of handover procedures based on in-band signaling instead of common channel signaling. These procedures have significant advantages compared with common channel signaling ones, specially when lossless handovers with in-sequence cell delivery are required. The possibility of combining in-band signaling handovers with common channel signaling necessary for other procedures was also discussed. The second contribution is related to performance analysis. The paper presented a simple analytical approach to evaluate the handover duration and other interesting performance measures; the analytical method was validated against results obtained through an event-driven cell level ATM simulator. The approach was applied to the proposed handover protocols, but can be used to evaluate any other procedures as well.

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