Handoff Prioritization and Decision Schemes in Wireless Cellular Networks: a Survey

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***Abstract*—Handoff is a key element in wireless cellular networks in order to provide Quality of Service (QoS) to the users and to support users' mobility. Handoff failure will result in the forced termination of an ongoing call. From the user's point of view, the service of a handoff request is more important, as the forced termination of an ongoing call is more annoying than the blocking of new calls. Therefore, in order to support QoS to the users and to provide ubiquitous coverage, the handoff procedure ought to be further investigated. This paper provides a comprehensive survey of the basic elements, the different types and phases of the handoff procedure. Moreover, particular interest has been given in the horizontal handoff execution phase by discussing and classifying the most recent handoff prioritization schemes into categories based on the concepts that these schemes adopt, e.g. Channel Reservation, Handoff Queueing, Channel Transferred, SubRating, Genetic and Hybrid Schemes and in the vertical handoff decision phase by presenting different decision algorithms.**

***Index Terms*— Cellular Networks, Handoff, Horizontal, Vertical, Resource Allocation, Prioritization Schemes.**

I. INTRODUCTION

CELLULAR radio is the fastest growing and most demanding area in the telecommunications industry. New generation cellular mobile radio systems, offering practicality and versatility and new mobile handsets supporting a range of innovative services and access to the mobile users, are the objectives and the main interests not only of the telecommunication companies, operators and providers, but also of the research community. The vision of "anytime, anywhere" communications is too close to become a reality.

In cellular mobile networks, the coverage region is divided into small services areas, known as cells. Each cell is covered by a Base-Station (BS), which serves the Mobile Terminals (MTs), i.e. users equipped with phones, within its region. Before a mobile user can communicate with other user(s) in the network, a group of the frequency bands or channels should usually be assigned. When a mobile user crosses the cell boundary or the quality of the wireless link is unacceptable, then the handoff process is initiated.

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Handoff is the process of changing the channel (frequency, time slot, spreading code, or combination of them) associated with the current connection, while a call is in progress [1]. Handoff is also referred in the literature as "handover" or as "Automatic Link Transfer" (ALT) [2].

With the penetration of the next generation wireless mobile networks and personal communication systems and the exploitation of the micro cell, pico cell and hybrid cell (macro-, micro-, pico-) architectures a new type of handoff has been occurred, the vertical handoff. Vertical handoff is the process of changing the mobile active connection between different wireless technologies. However, since these technologies have different characteristics, in terms of coverage, bandwidth and delay, handoff is a critical process and should be taken under careful consideration in order to ensure the continuity of connections and the QoS perceived by the users.

The scope of this paper is to provide the state-of–the-art overview of the basic elements and the different types and phases of the handoff procedure, to classify them and to discuss them accordingly.

II. HANDOFF PROCESS

In this section, the basic elements and procedures of the handoff are presented, such as the handoff phases, the types of handoffs and the metrics that are used for performance evaluation of the handoff scheme.

A. Types of Handoff

Handoffs may be classified based on several factors, like the type of the network, the involved network elements or the number of active connections and the type of traffic that the network supports. Such a classification is depicted in Table I.

Firstly, handoffs can be distinguished into horizontal and vertical, depending on whether a handoff occurs between a single type of network interface or a variety of different network interfaces. With the penetration of the next generation networks, vertical handoffs are a common phenomenon.

Horizontal handoffs in a cellular network can be broadly classified into intracell and intercell handoffs. Intracell handoffs occur when a user, moving within a cell, changes radio channels in order to minimize interchannel interference under the same BS [3]. On the other hand, intercell handoffs occur when an MT moves into an adjacent cell and therefore, all the MTs connections should be transferred to the new BS [3].

Vertical handoff is the process of changing the mobile active connection between different wireless technologies. Vertical handoffs can be further distinguished into *Downward Vertical Handoff (DVH)* and *Upward Vertical Handoff (UVH)*.

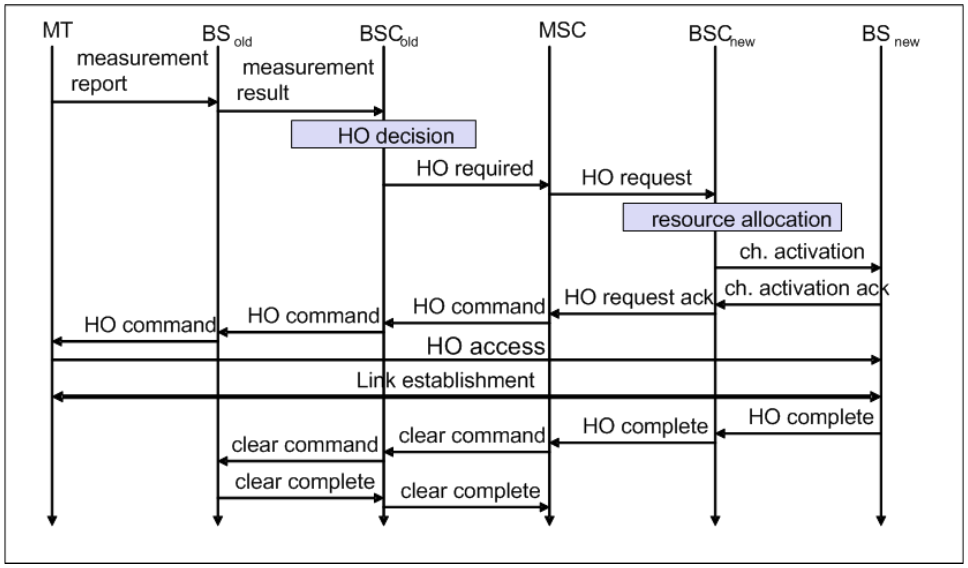

Fig. 1. Hard Handoff Process (redrawn from [8])

TABLE I
HANDOFF TYPES CLASSIFICATION

Types	Classification	
Horizontal	Intracell	Intercell
	Soft	Hard
Vertical	Downward	Upward
	Soft	Hard

In DVH the mobile user handoffs to the network that has higher bandwidth and limited coverage, while in UVH the mobile user transfers its connection to the network with lower bandwidth and wider coverage [4].

Handoffs can also be classified into hard and soft handoffs [5], [6] depending on which BS is serving the MT in the crucial period during handoff execution when there is a communication between the user in question with more than one BSs.

In the case of hard handoffs, an MT is served by only one BS (or by only one access network in the case of the vertical handoff) at a time. It contacts with the new BS or the new network only after having broken its connection with the serving BS. This is referred to as "break before make" connection. In hard handoffs, the data do not have to be duplicated and therefore, the data overhead is minimized. However, excessive service interruptions could result in an increased call dropped rate. Hard handoff is used by the systems, such as Global System for Mobile Communications (GSM) and General Packet Radio Service (GPRS) where Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) are applied [7]. Hard handoff is also the mandatory method to perform handoffs in the WiMAX (Worldwide interoperability for Microwave Access) technology [8].

The hard handoff process in the case of the GSM is illustrated in Figure 1 [8]. The MT needs to acquire information about the network in order to be able to perform the handoff. Then, handoff signaling messages are exchanged between the MT, the serving BS (BSold), the target BS (BSnew) and the Mobile Switching Center (MSC).

In soft handoff, the MT may be served by more than one BSs (or by one than one access networks). Soft handoff can be used to extend the time needed to take a handoff decision without any loss of QoS. However, since the data are transmitted to all links, frequent soft handoffs may result to an increased data overhead. The cellular Code Division Multiple Access (CDMA) systems use soft handoff techniques, due to the fact that in these systems a mobile node may communicate with more than one coded channels, which enables it to communicate with more than one BSs [7]. The soft handoff process between the MT and the BSs is illustrated in Figure 2.

A detailed overview, concerning soft handoffs in CDMA mobile systems, can be found in [10].

B. Performance Metrics of Handoff Schemes

Handoff is a key element in the wireless cellular networks, since its behavior has a direct impact on the overall performance, in terms of quality of service, resource utilization, and signaling load. The handoff strategy is determined by the so-called handoff schemes. Several metrics are used to evaluate the performance of a handoff scheme, such as:

- **New (or originating) call blocking probability:** It is defined as the probability that a new call attempt is to be blocked.
- **Handoff call blocking or handoff blocking probability:** It denotes the probability that a handoff attempt is to be blocked.
- **Handoff probability:** It denotes the probability that a handoff is to occur during a call.
- **Call dropping or forced termination or interrupted call probability [9]:** It denotes the probability that an ongoing call is going to be prematurely terminated.
- **Delay:** It denotes the time interval between the initiation of a handoff request and the execution of the handoff request.

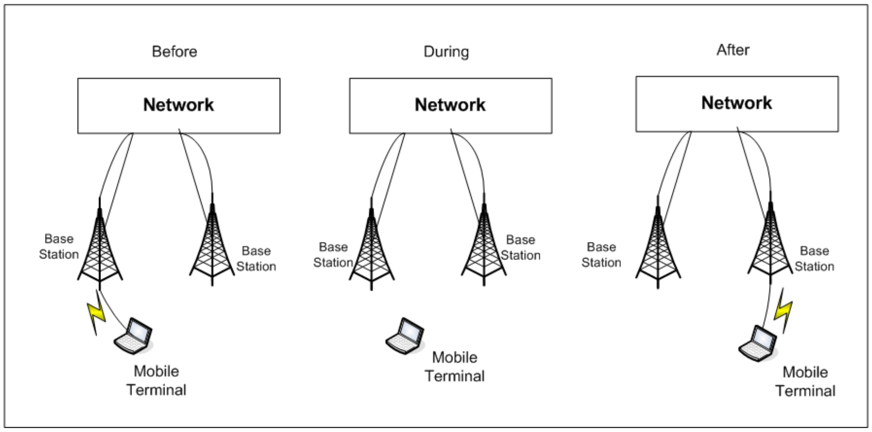

Fig. 2. The Soft Handoff Process

- **Channel utilization efficiency:** It is defined as the ratio between the mean number of channels that are being served and the total number of channels in the system.

III. Horizontal Handoff Process

A. Handoff Phases

The horizontal handoff procedure may be distinguished in the following four phases [11], [12]:

- **Measurement:** During this phase link measurements (e.g. Received Signal Strength (RSS), Signal to Interference Ratio (SIR), distance measure, Bit Error Rate (BER)) are carried out at both parts: the BS and the MT ([11], [13]).
- **Initiation:** The objective of this phase is to decide whether a handoff is needed and if so, to initiate the process. Handoff process should be accomplished, whenever the received signal quality deteriorates inside a cell, or between two adjacent cells, or when the MT is moving along the common boundary of two cells. Several signal strength methods for handoff initiation may be found in [5] and [14].
- **Decision:** The objective of this phase is the selection of the new channel, taking into account the actual resource availability and the network load. The decision-making process of handoff may be centralized or decentralized (i.e., the handoff decision may be made at the MT, or at the network). From the decision process point of view, one can find at least three different kinds of handoff decisions [5]:
  - **Mobile-Controlled HandOff (MCHO):** In the MCHO handoff, the MT continuously monitors the signals of the surrounding BSs and the interference levels on all channels. A handoff can be initiated if the signal strength of the serving BS is below a threshold, where the call can be served by another BS. The MT requests from the target BS a channel with the lowest interference. This type of handoff has a short reaction time (of the order of 0.1 second). MCHO is used in DECT (Digital Enhanced Cordless Telecommunications) standard.
  - **Network-Controlled HandOff (NCHO):** In the NCHO, the surrounding BSs measure the signal from the MT. The network initiates the handoff process, when some handoff criteria are met, e.g. the level of SIR, of the BER based on the measurements of the previous phase. Network-controlled handoff is used in first-generation analog systems, such as AMPS (Advanced Mobile Phone Service), TACS (Total Access Communication System), and NMT (Nordic Mobile Telephony).
  - **Mobile-Assisted HandOff (MAHO):** In the MAHO, the network requests the MT to measure the signal from the surrounding BSs. The network makes the handoff decision based on reports from the MT. MAHO is used in the GSM (the handoff time between handoff decision and its execution is approximately 1 second) and in cdmaOne or IS-95 CDMA.

  More details concerning the three different decision strategies can be found in [15].
- **Execution:** In this phase, the network allows an MT, which communicates with a BS in one of its cells, to transfer its communication into another channel or another cell. During this phase, the over-the-air and network process signaling is performed, as well as, authentication, database lookup and network reconfiguration.

B. Handoff Schemes

Handoff in a wireless network is a key element in order to ensure the continuity of connections and the QoS perceived by users. As a consequence, since the handoff process is managed by the so-called handoff schemes, the main interest is focused on them. The handoff schemes that may be found in the literature can be broadly classified into Non-Prioritized and Prioritization Schemes (Figure 3) [14]-[16], [18]-[88]. The Non-Prioritized (NPS) Scheme [16] has been employed by the typical radio technologies proposed for the Personal Communication Systems (PCS) operating at the band of 2 GHz. This scheme does not differentiate handoff and initial (new or originating) request calls. Thus, either an originating or a handoff call request will be served, as long as, there is a channel available in the cell. If there are not any free channels, the request is blocked immediately. The main disadvantage of this scheme is that, since no priority is given to handoff request

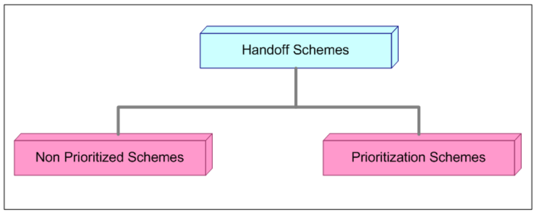

Fig. 3. Classification of the Handoff Schemes

calls over originating calls, the forced termination probability is relatively higher than it is normally anticipated [16], [17].

Since the wireless bandwidth is limited, an efficient handoff scheme should allow a high utilization of the wireless channel capacity; while at the same time it should preserve the QoS of handoff calls, mainly by minimizing the call blocking probabilities, the transmission delay and the call dropping probabilities. However, all these requirements cannot be satisfied simultaneously, and therefore, tradeoffs between all of them are carried out. From the users perspective, the termination of an ongoing call is more annoying than the blocking of a new call [18]-[19],[77]-[78]. Consequently, the handoff blocking and the forced termination probabilities ought to be minimized. To achieve these requirements several handoff prioritizing schemes have been proposed [14]-[16], [18]-[88].

The basic concept of all handoff prioritization approaches is to give handoff requests precedence over the new session requests in some way [19]. Handoff prioritization schemes provide improved performance at the expense of a reduction in the total admitted traffic and an increase in the blocking probability of new calls [20]. However, the improvement in performance is related with the way that each scheme gives priorities to handoff calls.

Therefore, several handoff prioritization schemes, that support different services and different traffic requirements, may be found in the literature. These handoff prioritization schemes may be further classified into Channel Reservation, Handoff Queueing, Channel Transferred, SubRating, Genetic and Hybrid, as it is depicted in Figure 4.

C. Channel Reservation Schemes (CRS)

Channel Reservation handoff Schemes (CRS) offer a method to achieve successfully handoff requests by reserving a number of channels exclusively for handoff requests. These schemes can be further divided into static and dynamic reservation schemes, depending on whether the set of reserved channels is fixed or varies according to the actual handoff resource demand. This classification of the channel reservation schemes is depicted in Figure 4.

1) Static Channel Reservation Schemes (SCRS): The Static Channel Reservation Schemes (SCRS) set fixed thresholds in order to guarantee that the proper bandwidth will be allocated to a handoff call, in order to fulfill its service requirements. Further, the static channel reservation schemes may be distinguished in Guard Channel and Threshold Priority Schemes ([21], [22]) (Figure 4).

The Threshold Priority Schemes (TPS) or New Call Bounding Schemes (NCBS) ([21]) ensure the priority of the handoff calls by limiting the number of admitted new calls to the system by a predefined threshold [22]. If the number of the admitted new calls in a cell exceeds a threshold, when a call arrives, the new call is blocked. A handoff call is rejected only when there is no available channel in the system. This scheme performs well in heavy traffic load environments, since the new call bouncing scheme could handle the problem by spreading the potential bursty calls (users will try again, when the first few tries fall) [21].

On the other hand, in the Guard Channel Schemes (GCS), also referred as Cut-Off Schemes, a number of channels are reserved a priori for handoff calls ([14], [23]). The remaining channels are shared equally between new and handoff calls.

Although the first guard channel, proposed by Hong *et al*. in [23], assumed that the call holding time and the cell dwell or residence time are exponentially distributed, recent studies proved that this assumption is correct under certain conditions. Lin *et al*. in [16] proved that the channel holding time is exponentially distributed only if the cell residence time is also exponentially distributed. Guerin in [24] showed that when the rate of the direction change is "low", the channel holding time is no longer exponentially distributed. Rajaratnam and Takawira [25] proved that blocking probabilities are indeed sensitive to the assumption on handoff traffic and thus, the Poisson assumption is not appropriate.

Therefore, several different performance evaluations of the guard scheme [23] were presented under different assumptions concerning the call holding time and the cell dwell or residence time ([25], [26]-[30]). Guerin in [24] assumes that the call holding time, and the channel holding time are all exponentially distributed. In [26], Fang *et al*. use a general distribution to model the call holding times and derive general formulas for the call completion probability and the expected effective call holding times of both complete and incomplete calls. Orlik and Rappaport [27] modeled the cell residence time as a Sum Of HYper-exPonential (SOHYP) random variable while Fang and Chlamtac [28] as a hyper-Erlang random variable. Zhang and Soong [29] consider that the handoff dwell time is following a truncated Gaussian distribution. Finally, in [30] call holding time, cell residence time, channel holding time, and inter-service time are assumed to be generally distributed. From the obtained results, the authors in [28] also observed that in order to appropriately characterize the channel holding time, a good mobility model is required; a mobility model that has at least the following two conditions:

1) it must be simple but good enough to fit field data and
2) the resulting queueing system model must still be tractable.

Also, an extension of the guard channel is proposed in [31]. In this scheme, the new calls are allowed to be queued until new channels are obtained in the cell. This method increases the total carried traffic, since all the traffic that would be carried in a system without guard channels still will be carried in the system. For example, for a system with 44 channels and 30 and 8 type I (handoff) and type II users (new) respectively,

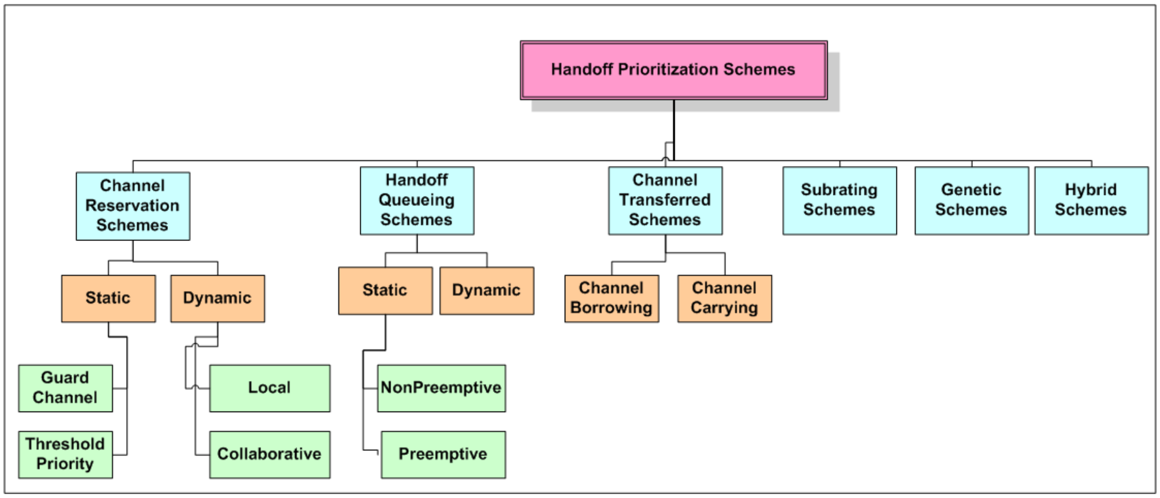

Fig. 4. Classification of the Handoff Prioritization Schemes

the obtained gain in total carried traffic by queueing the type II users is about 2.4 Erlangs.

In the GoS based Channel Reservation Scheme (GoSCRS) the authors in [32] proposed a new technique in order not only to give priority to handoff calls, but to protect the originating calls and to keep the system capacity at an acceptable level. The idea is to divide the total bandwidth in two groups, one exclusively for handoff calls and the other for both handoff and originating calls. The ratio between the originating calls and the handoff calls in the second group, as well as the capacity of each group are defined based on a genetic algorithm that tries to find the optimal thresholds, in order to balance the GoS for handoff calls and new calls and at the same time to minimize the system cost. Numerical results showed that the proposed scheme achieves better performance than the GCS proposed in [23] in terms of call incompletion probability.

The guard schemes have proven to be effective for providing the necessary QoS guarantees in both call termination and call blocking probabilities in single-service wireless cellular networks [33]. In order to apply this approach into multi-service or integrated wireless environments, several policies have been proposed to ensure fairness among services and to satisfy the different prioritization level requirements of each service ([33]-[36]).

In [34], the authors extended the guard channel scheme in multi-service networks. The proposed scheme is very general since each type of traffic can request different QoS in terms of a variety of system parameters, and finite buffers are used for both new arrivals and handoffs. Simulation results showed that, in the case of three different classes with different bandwidth requirements, as incoming handoff call rates increase the class that requires a greater number of channels is affected more. However, the analysis is based on the assumption that the different types of traffic are independent and also that each traffic threshold affects the performance of other traffic types in the system.

In [35], the Complete Sharing (CS) and the Complete Partitioning (CP) policies are presented (Table II). The CS policy allows all users to have equal access to the available bandwidth at all times. The CP policy, on the other hand, divides up the available bandwidth into separate sub-pools according to user type. The authors studied the performance of these policies in macrocell, as well as, in microcell systems. The obtained results in the macrocell system, where most of the traffic is produced by new calls, showed that under heavy loads CS achieves better performance than the CP policy in terms of channel utilization and new call blocking probability. However, in the case of microcells, where most the traffic is handoff calls, in heavy traffic loads, the CP policy prevents the starvation of lower priority calls. Also, in both scenarios simulation results showed that under light loads the channel utilization of the different policies is essentially the same.

An extension of the CP policy is the concept of the movable boundary approach for homogeneous Personal Communication Systems (PCS), that it was initially proposed by Haung *et al*. [36]. The key idea of this approach is to divide the available bandwidth of each cell into dynamically adjustable bandwidth compartments, the size of which could vary according to the each time traffic requirements. This dynamic partition adjustment increases the bandwidth utilization, facilitates the provisioning for different QoS requirements and can effectively deal with the traffic change [37]. A variation of the movable boundary approach is presented in [33], called the Dynamic Partition (DP) approach, in order to consider different bandwidth requirements for each traffic type. Simulation results showed that in the case of two different types of traffic (voice and data) the highest utilization is achieved when there are no channels reserved exclusively for data calls.

2) Dynamic Channel Reservation Schemes(DCRS): In the DCRS, each BS dynamically adapts the channels reserved for handoff requests based on the variation in system parameters (e.g. traffic conditions and the position of users). This will enable the BS to approximately reserve the actual resources and thereby to accept more new connection requests compared to a fixed scheme ([38]-[39]).

Dynamic Reservation Schemes (DRS) can be further distinguished into Local and Collaborative [19] (or Distributed [68]) Schemes depending on the way they obtain the required information for the variation in the system parameters: Local information is used by the BS or information is obtained from

TABLE II
COMPARISON OF DIFFERENT POLICIES

Policy	Advantages	Drawbacks
Complete Sharing	Maximization of the channel utilization	Fairness and QoS among different types of services are not retainable
Complete Partitioning	Prevention of starvation at the time of congestion Isolation between each type	Not suitable for light traffic cases

TABLE III
DETERMINATION OF THE DYNAMIC FOR THE NEW CALLS FOR THE FGC VARIATIONS

Scheme	System Parameters
Fractional Guard Channel Scheme	The total number of admitted new calls
Thinning Scheme II	The number of new calls in service
Dynamic Channel Reservation Scheme	The request probability of new calls

the neighboring BSs. A detailed classification of the DRS can be found also in [19], in [68] and in [89].

Local Channel Reservation Schemes (LCRS) adjust the number of reserved channels according to the variation of the system parameters (e.g. the current handoff dropping rate, the traffic conditions and the position of users), by only using locally available information ([42]-[45]).

For example, Oliveira *et al.* in [42] calculate the number of channels to be reserved according to the requested bandwidth of all ongoing connections or according to the number of ongoing connections. Each BS keeps monitoring the handoff call blocking probability and the utilization of channels in its cell, and then it uses this information to adjust the reservation accordingly. Simulation results showed that the proposed scheme provides small handoff dropping probability in neighboring cells and achieves high bandwidth utilization. More specifically, comparing this scheme with two other schemes that both do not reserve bandwidth in the neighboring cells and their only difference is that the first one reassigns bandwidth from the lower class resulted in significantly savings (66% and 89% respectively) in the handoff dropping probability.

Another representative scheme of this category is the Fractional Guard Channel Scheme (FGCS), proposed by Ramjee *et al.* [43]. In this scheme, the total number of the admitted new calls is dynamically adjusted according to a random number, between zero and one, which depends on the current channel occupancy. The advantage of FGCS scheme is that it distributes the newly accepted calls evenly over time which leads to a more stable control [47]. Simulation results showed that FGCS scheme resulted in significant (from 20% to 50%) savings in the new call blocking probability over the GCS scheme for the MINBLOCK problem (minimizing the new call blocking probability with a hard constraint on the handoff call blocking probability) and provided some small improvement over the GCS scheme for the MINC problem (minimizing the number of channels subject to hard constraints on the new and handoff call blocking probabilities).

Several extensions of the FGCS scheme may be found in the literature ([21], [44]) based on which system parameter is used to determine the threshold for the new calls (Table III). In the Thinning Scheme II [21], the threshold for the new calls is determined by the number of new calls currently in service. More specifically, a new call is admitted with probability a_i if there are i new calls currently in service, and all calls will be blocked if all channels are busy.

The Channel REservation Scheme (CRES) [44] is also a particular case of FGCS. In this scheme, new calls are allowed to use guard channels based on a random factor: the request probability. The request probability of the new call is adaptively determined according to the mobility of calls, the total number of channels in a cell, the threshold between normal channels and the guard channels, and the current number of used channels. Even though guard channels are reserved for handoff calls, they can be allocated to new calls according to the request probability in order to increase channel utilization. Simulation and analytical results indicated that CRES presents a better channel utilization than the GCS and achieves lower blocking probabilities than the GCS. More specifically, when the number of reserved channels is small the performance of the CRES is slightly better that of the GCS. However when the number of reserved channel is big (e.g. 11), the average blocking probabilities and channel utilization are 7.3% lower and 3.1% higher than the ones for the GCS scheme for the same threshold.

In order to apply the dynamic approach into multi-service environments, the authors in [45] proposed the Dynamic Guard Channel Scheme (DGCS). In this scheme, a number of channels are reserved for high priority services. The channel threshold of each service is dynamically adjusted according to the traffic load. The simulation results show that the ratios among different QoS service probabilities are guaranteed to predefined values and the system utilization is improved. Also, the results showed that the channel utilization of DCRS is higher than that of GCS for the same threshold and that the channel utilization of DCRS is getting better than that of GCS when the offered load is being increased. The Collaborative Channel Reservation Schemes (CCRS) on the other hand, determine the number of reservation channels mostly based on BSs exchange information or on mobility prediction and a location system, in order to be informed regarding the resource usage in neighboring cells [19]. Several collaborative channel reservation schemes may be found in the literature ([18], [37], [45]-[52]).

The Mobility based Reservation Scheme (MRS) proposed in [39] introduces the concept of the influence curve to characterize the influence that an ongoing call exerts on the adjacent cells, since an ongoing call in one cell may have potential impact on the resource usage of another cell. According to the influence curve, the number of channels needed to be reserved in each cell can be determined and thus the channel reservation can be adjusted dynamically. Moreover, to overcome potential congestion, a new call bounding scheme is introduced, in order to place a direct limitation on the number of the new calls admitted to a cell. Simulation results showed that the proposed schemes are more effective in providing better QoS for the handoff calls with slight degradation of new calls.

The Distributed Call Admission Scheme (DCAS) introduced by Naghshineh and Schwartz [46] calculates the maximum number of calls that can be admitted to a given cell without violating the QoS of the existing calls in the cell, as well as, calls in its adjacent cells. One of the main features of the DCAS is its simplicity, since the admission decision can be made in real-time and without requiring much computational effort [47]. However, in this model, all connection requests have identical traffic profile and the traffic is assumed to be under stationary conditions. Moreover, the DCAS cannot always guarantee the target call dropping probability, as it is shown in [47]. This is due to a number of simplifying approximations in the control mechanism used in the DCAS, which potentially can lead to imprecise control decisions.

The Stable Dynamic Call Admission (SDCA) control mechanism is proposed in [47]. This scheme requires periodic exchange of information, such as channel occupancies and call arrival rates, between the BSs of the neighboring cells, in order to determine the fraction of new calls that will be admitted for the next control period. The main advantage of this scheme is that, in contradiction with the GCS and the DCAS, it can enforce QoS guarantee for the dropping probability.

The Shadow CLuster Scheme (SCLS) introduced by Levine *et al*. [48], is based on the idea that "every MT with an active wireless connection exerts an influence upon the cells (and their BSs) in the vicinity of its current location and along its direction of travel". The size of a shadow cluster, for a given active MT, mainly consists of the cell, where the mobile is currently present (i.e. the center of the shadow cluster) and all its adjacent cells along the direction of the travel. This area changes when the mobile call is handed off to other cells and thus, a tentative shadow cluster needs to be implemented for every new call, as well as, and/or every handoff call [47]. Simulation results showed that the shadow cluster mechanism is able to reduce the percentage of dropped calls from 14% to 1% in a controlled fashion. The efficiency of this scheme depends on the knowledge about the dynamics of an MT, such as its position, velocity, acceleration and its call holding patterns that are hard to be predicted and moreover require large computational effort [47]. However, it is difficult to accurately estimate all these movement patterns.

Aljadhai and Znati [49] proposed the concept of the Most Likely Cluster Scheme (MLCS) to support predictive timed-QoS guarantees in wireless networks. The Most Likely Cluster (MLC) is a set of cells that are the "most likely to be visited by a MT during its lifetime". The shape of the MLC and the number of cells in the MLC are determined based on the moving speed and the direction of the MT. Simulation results showed that the MLCS scheme achieves a balance between guaranteeing an uninterruptible service for admitted calls and maximizing the utilization of the network resources. Also, in comparison with the SCLS scheme, the MLCS achieves lower call blocking probabilities and higher utilization as the network load increases. However, the drawback of this scheme is that since a number of cells need to reserve bandwidth before admitting a new connection, this approach, either wastes a large amount of bandwidth, or may not well adapt QoS target for the connection dropping rate [50].

A variation of the MLCS called the Differential Bandwidth Reservation Scheme (DBRS) is presented in [50]. The DBRS scheme adapts the cluster approach of the MLCS. However, in this scheme, the cells in the cluster are further divided into two regions, depending on whether they have an immediate impact on the handoff or not. Moreover, in order to keep the call dropping probability below a predefined-threshold, the authors proposed an admission control mechanism that is adaptable to the mobility pattern of the MT in terms of the sector size, number of cells in the cluster and specific QoS. The admission control algorithm is applied only to a subset of the cells in the sector, in order to examine whether the required connection dropping rate can be maintained. Simulation results showed that DBRS provides comparable call blocking probability with the CGS and lower call blocking probability with the CGS. Also, the DBRS maintains a stable call dropping probability, while for both the GCS and the MLCS schemes the call dropping probability increases with the workload.

In Choi's scheme [51], the BS calculates the required bandwidth to be reserved for the handoff calls from the neighboring cells. The mobility of the mobile user is estimated using a history recorded in each cell. Using this information, the scheme predicts the handoff time and the amount of bandwidth that should be reserved. The BS adjusts the amount of reserved bandwidth by changing the size of the estimation window, depending on the handoff failures recorded. Also, based on the number of the BSs that participate in the admission decision of a new request call, three different policies are proposed. Simulation results showed that the proposed scheme achieves to keep the dropping probability below a predefined threshold. The authors also stated that the proposed scheme is more realistic than the DCAS and the SCLS for the following reasons:

- In the DCAS and the SCLS exponentially-distributed mobile sojourn times are not assumed;
- Mobility estimation time window control allows inaccuracy in mobility estimation and in time-variation of traffic/mobility
- It is not required to determine the optimal value of parameters.

The Predictive Channel Reservation Scheme (PCRS) [52] is based on the current position, the velocity and the orientation of an MT. By using this information, the system can estimate where the mobile device will cross the cell boundary (on the condition that the call has not been terminated by that time) and hence determine the new potential BS. Once the MT is within the range of the new cell, the currently serving BS sends a channel reservation request to pre-allocate a channel in the cell for the imminent handoff. The PCRS scheme, in general, pre-allocates only one channel as a result of the prediction. This is a major advantage, since channel availability is not degraded. The computational overhead involved in the prediction part of the scheme is minimal, due to the fact that a simple dead reckoning algorithm is employed to carry out the extrapolation. According to the author, this algorithm is not computationally intensive, and therefore, it should not be regarded as a drawback of the scheme. However, the

TABLE IV
RESERVATION SCHEMES COMPARISON

Scheme	Advantages	Disadvantages
Static	Simplicity	Inflexible to traffic change situations
Dynamic	Flexible to traffic change situations	Computational and signaling overhead

fact that the PCRS does not use road information, in some situations (when the MT changes direction) could lead to invalid reservations in the sense that the MT can deviate from its predicted path and move toward a different neighboring cell [53].

The Road-Map-based Channel-Reservation Scheme (RMCRS) [53] is a predictive reservation scheme restricted by the layout of the roads and traffic regulations. This scheme makes use of the mobile users moving speed, its direction, and the road information stored in the BSs to predict the handoff probabilities to neighboring cells. The amount of reserved bandwidth is dynamically adjusted according to the handoff probability and the traffic load in each cell. Simulation results show that RMCRS achieves resource efficiency within an acceptable level of handoff-dropping and new-call-blocking rates. Furthermore, RMCRS is robust under different traffic conditions and various layouts of roads.

In [54], the proposed Predictive Reservation Scheme (PRS) is based on the assumption that each MT is equipped with reasonably accurate positioning capability and that each BS maintains a database of the roads within its coverage area. By using this information, each BS may perform predictions for all active mobile terminals in its service area to dynamically adjust according to the resource demands of mobile terminals that are anticipated to handoff into the cell from the neighboring cells. Simulation results proved that mobility prediction schemes, based on mobile positioning information, are more accurate, leading to more efficient reservations in comparison with the Choi's AC1 scheme [51] in the case of a 2D-cell layout.

The advantages and the drawbacks of the static and dynamic channel reservation schemes are summarized in Table IV.

D. Handoff Queueing Schemes (HQS)

HQS allow either the handoff to be queued [55] or both the originating calls and handoff requests to be queued [56]. The HQS schemes give priority to handoff attempts by permitting them to be queued, instead of denying the access in the potential new BS if it is busy. This is possible due to the time a mobile device spends in the overlapping service region of the cells, called the handoff area. If an MT is in the handoff area and the destination cell has no free channels, then the MT maintains its communication with the source cell. The handoff request is queued and sent to the BS of the destination cell. If a channel, in the destination cell, is available before the MT crosses the handoff area, then the channel is assigned to the MT. Otherwise, the call is terminated in a forced way ([14], [23]).

As stated in [15], queueing is effective only when handoff requests arrive in groups and traffic is low, since if handoff requests occur uniformly, queueing is not needed. By applying the queueing policy in the handoff schemes, the probability of forced termination is decreased at the expense of higher new call blocking. This is achieved due to the fact that channels are not assigned to new calls until handoff requests in the queue are served.

Queueing schemes, as Figure 4 depicts, can be further distinguished into static and dynamic schemes. The static (or FIFO) schemes are served in First Come-First Served (FCFS) manner. On the other hand, dynamic schemes take into account the different system parameters, and dynamically reorder handoff requests in the queue to reduce the probability of forced termination.

1) Static Handoff Queueing Schemes (SHQS): There are two general policies in the static priority queueing disciplines: preemptive or non-preemptive. A non-preemptive queueing discipline requires a call that begins service to complete its service without interruption. In a preemptive priority queue, if a call, arriving at the queue, finds a call of lower priority in service, then the arriving call preempts the lower priority call to the queue and begins service immediately. A preempted call will resume the service, at the point at which its service was suspended, as soon as there are no higher priority calls remaining in the queue. A preemptive scheduling policy with this latter property is called preemptive resume. Several static handoff queueing schemes may be found in the literature ([57]-[59]).

Chang *et al.* [57] proposed a priority scheme that allows finite queueing of both new and handoff calls, in two separate FIFO queues. Moreover, the authors considered the reneging of new calls and dropping of queued calls as they move out of the handoff area, before the handoff call is successful. Optimal cutoff parameters and appropriate queue sizes that minimize overall blocking probability are found numerically.

A Modified FIFO Scheme (MFIFOS) is proposed in [58]. This scheme, as Figure 5 depicts, allows both the new calls and handoff calls to be queued in order to obtain a better call completion probability. Since the proportion of the handoff calls and the new calls will influence the call completion probabilities, in general, the authors proposed also the Rationed Channel Assignment Scheme (RCAS), where the ratio of the handoff to initial calls is adjusted dynamically to a pre-determined value. Simulation results showed that both the MFIFOS and RCAS are better than the NPS scheme and the FIFO scheme in terms of call incompletion probability and new call blocking probability.

Handoff queueing schemes for GPRS networks are proposed in [59]. The authors implemented priority queues to give transmission priority to packets requiring shorter transmission latency at the cost of longer mean waiting times and system times for non-priority packets. More specifically, the improvement on mean waiting time and system time for priority packets over the FIFO queueing scheme can be as large as 0.025 seconds when the priority packet arrival rate is the 32 packets/sec, the transmission delay can be greatly reduced to an extend of nearly 72%.

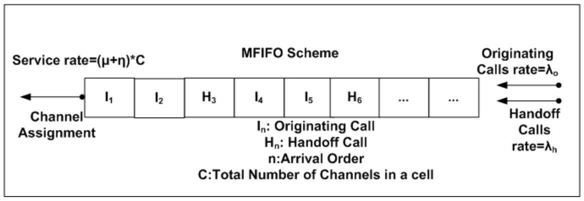

Fig. 5. The MFIFO Scheme

E. Dynamic Handoff Queueing Schemes (DHQS)

DHQS take into consideration the different system parameters, and dynamically reorder the handoff requests in the queue in order to reduce the probability of forced termination. Dynamic reordering is necessary, since the handoff requests need to be queued in a way to reflect the dynamics of the user motion (i.e., the change of his moving speed).

Tekinay and Jabbari [55] proposed the Measurement-Based Prioritization Scheme (MBPS), where a handoff request call in the queue with the lowest Received Signal Strength (RSS) gets served, when a channel is released. The simulation and the analysis results indicate that the proposed scheme outperforms FIFO queueing scheme in terms of QoS and bandwidth utilization. However, this study does not take into account the dynamics of user motion, (i.e., the MTs different velocities, users stops in traffic lights etc) [62].

Ebersman and Tonguz [60] propose the Signal Prediction Priority Queueing Scheme (SPPQS) in order to improve the MBPS scheme. In this scheme, the determination of the priority ordering in the handoff queue is based on the RSS and its change (ΔRSS). The results showed that SSPQS scheme achieves smaller forced termination probability than FIFO queueing and MBPS. More specifically, simulation results showed that in a PCS environment, for realistic call blocking probabilities (from 2% to 6%), SPPQS leads to about 15% fewer dropped calls compared to SHQS (queue only for handoff calls). However, this happens at the expense of a slight increase ($\prec$ 1%) in the new call blocking probability. Also, simulation results showed that the SPPQS outperforms the MBPS, in cases when the MT changes often velocity, stops at traffic lights, or turns a corner resulting in the "street-corner" effect.

For multimedia wireless networks, the dynamic priority queueing is achieved by the Signal Strength for Multimedia Communications Scheme (SSMCS) proposed by Chang and Leu [61]. In the SSMCS scheme, the priority ordering in the handoff queue is based on the service priority, the ΔRSS and the RSS itself. The simulation results show that the SSMC scheme can reduce handoff call dropping probability for every service class and that has shorter handoff processing delay in comparison with the FIFO scheme. However, this strategy can reduce about 15% the handoff dropping probability for the highest priority class in comparison with a NPS scheme. However, this happens at the expense of the new call blocking probability. Also, simulation results showed that the SSMCS achieves similar new blocking probability than a SHQS (queue only for handoff calls). However, the SSMCS has shorter handoff processing delay.

Furthermore, Xhafa and Tonguz [62] proposed an analytical framework for dynamic priority queueing of handoff calls in wireless networks. More specifically, they consider two classes of priority handoff calls and two queues are used, one for each handoff class. The priority ordering in the each queue is based not only on the RSS, but also on the remaining time in the overlap region between two cells. Therefore, under certain conditions (i.e. when the remaining time in the handoff area for the second priority handoff call is the same with the one that first priority handoff calls spend in the handoff area) a handoff request call, waiting in the second-priority queue, may become a first priority handoff request call to join the first- priority queue. The queueing model of the proposed framework is depicted in Figure 6. More specifically, the authors assumed that there are C channels available per cell and two finite storage queues (H1 for the first and H2 for the second priority). If a handoff request, belonging to the first (second) priority queue, finds H1 (or H2) requests in the queue, this call is blocked; otherwise, it joins the queue it belongs to (i.e. Q1 or Q2). Simulation and numerical results show that, under certain conditions, the developed framework can analyze the performance of other queueing schemes, such as SQHS and hybrid static queueing and guard channels schemes. More specifically, when the transition rate for a second-priority handoff call from the second-priority queue to the first-priority queue is close to zero the proposed framework converges to the *Chang et al.* [57]'s scheme, while this rate goes to infinity the proposed framework converges to a SHQS scheme.

Finally, Lin and Lin proposed the Quality Prediction Priority Queuing Scheme (QPPQS) [63], where the priority ordering in the queue is based on its current Packet Success Rate (PSR), the PSR degradation rate, and the minimum PSR requirement of its service class. The results showed that the QPPQS is more suitable for multimedia communication networks and performs the best compared to the SSMCS and the FIFO schemes. More specifically, simulation results showed that, although in light traffic load every handoff ordering methods perform the same, in heavy load environments the call dropping probability for the higher priority class is reduced approximately about 10% when compared to a system that uses the SSMCS approach.

Table V summarizes the characteristics of several dynamic priority queueing schemes, depending on their priority ordering criteria, the number of services that each scheme supports if the user mobility dynamic is taken into account.

F. Channel Transferred Handoff Schemes (CTHS)

The key issue of this category is that in case that there are no available channels to accommodate a handoff call request, a channel from a neighboring cell may be transferred. Upon handoff, the selection of the transferred channel may follow the two decision categories: the Channel Carrying Approach (CCA), that selects its current channel to carry it in the destination cell, and the Channel Borrowing Approach (CBA), that selects a new channel from the neighboring cells. This classification is depicted in Figure 4.

1) Channel Carrying Handoff Schemes (CCHS): The CCHS allows the MT to carry its channel under certain

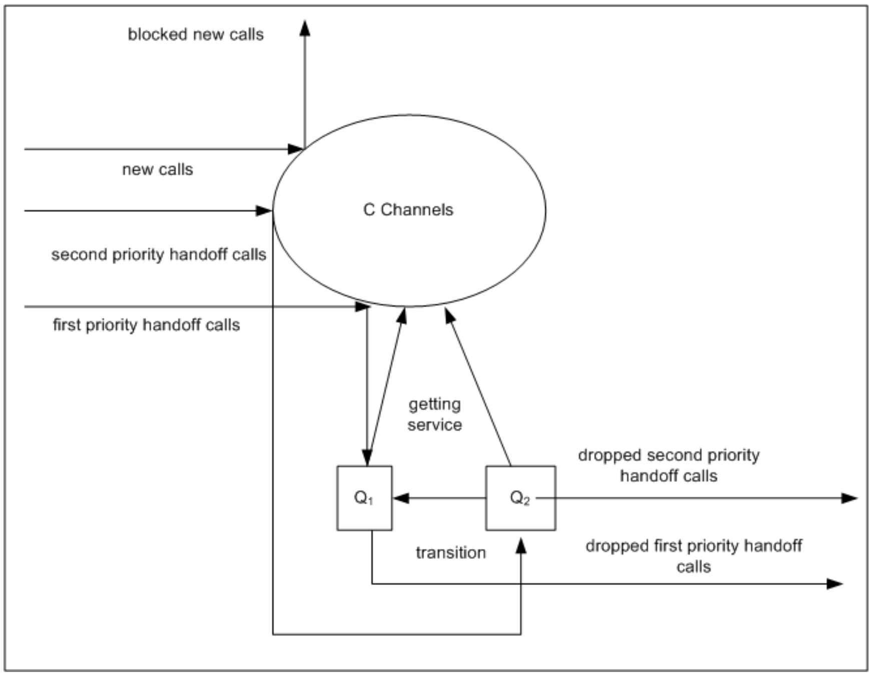

Fig. 6. The Xhafa *et al.* 's queueing model (redrawn from [62])

TABLE V
DYNAMIC PRIORITY QUEUEING SOLUTIONS AND THEIR CHARASTERISTICS

	MBPS	SSPQS	SSMCS	Xhafa framework	QPPQS
Priority Ordering Criteria	RSS	RSS, ΔRSS	RSS, ΔRSS, type of service	RSS, ΔRSS, waiting time in queue	current PSR, the PSR degradation rate, and the minimum PSR of its service class
Service Dimension	Single service/class	Single service/class	Multiple service/class	Two service/class	Multiple service/class
User Mobility Dynamic is considered	No	Yes	Yes	Yes	Yes

mobility patterns from its current cell into the new cell, without violating the minimum reuse distance requirement. Thus, communication is now maintained via the BS in the new cell using the old channel [65]. Simulation results showed that in linear cellular systems the CCHS scheme outperforms the GCS scheme, resulting in the linear (1-D) case in over 50% better network utilization than the GCS scheme.

2) Channel Borrowing Handoff Schemes (CBHS): The CBHS was proposed by Engel *et al.* [66]. The key issue of this approach may be summarized as: an acceptor cell, that has used all its nominal channels, is allowed to borrow free channels from its neighboring cells (donors), to accommodate new calls. A channel can be borrowed by a cell if the borrowed channel does not interfere with existing calls. When a channel is borrowed, several other cells are prohibited from using it. This is called channel locking. The number of such cells depends on the cell layout and the type of initial allocation of channels to cells ([20], [66], [67]). A further classification of the borrowing schemes can be found in [20].

G. SubRating Schemes (SBRS)

The SubRating Schemes degrade the bandwidth of an existing call in order to accept more handoff calls. More specifically, in theses schemes, some ongoing calls may be forced to operate under a degraded mode in order to accommodate more calls in an overloaded system [69].

The concept of the SubRating scheme was proposed by Lin *et al.* in [70]. In this scheme, certain channels are allowed to be temporarily divided into two channels at half the original rate in order to accommodate handoff calls. By applying this scheme, the one half of the original channel can be used to serve the existing connection and the other one to serve the handoff request so that the forced termination of calls can be virtually eliminated. It should be noticed that the channel SubRating mechanism is activated only if all the channels are occupied upon a handoff request arrival. When a subrated channel is released, it is transformed into an original full-rated channel by being combined with another sub-rated channel. The SBRS scheme reduces the blocking probabilities and the forced termination probability for handoff calls at the expense of introducing degradation in the system [71].

A modification of the SubRating scheme is also proposed in [72]. More specifically, the authors considered two classes: The wideband class, which is assumed to be an adaptive QoS class that accepts channel SubRating, and the narrowband class that does not accept QoS degradation. New calls, belonging to both classes, are only accepted if and only if the scheme can ensure the total requirements in bandwidth for the call, otherwise the call is blocked. Simulation results showed that the proposed scheme outperforms the GCS scheme in terms of call blocking probability and utilization. Also, the simulation results showed that, for low levels of traffic load, the duration within which the QoS degraded remains under 3.6% of the total call duration. However, as the traffic load increases the wide-class (the class the channels of which are sub-rated) calls experience longer periods of degraded QoS and also the delay increases.

H. Genetic Handoff Schemes (GHS)

The Genetic Algorithm Scheme (GAS) was introduced by Yener and Rose in [73]. This scheme uses genetic algorithms [74], in order to assign the channels using local state-based call admission double-threshold policies. In this case, a BS only keeps track of the state information of a small number of cells and makes decisions based on the abbreviated state information.

The authors also proved that the GAS finds better admission policies compared with other well-known methods of handoff reservation for both one-dimensional (1-D) and two-dimensional (2-D) (Manhattan model) cellular networks. However, the time needed to assign channels for the GAS scheme is the main drawback of this scheme [58].

I. H. Hybrid Handoff Schemes (HHS)

Hybrid Handoff Schemes (HHS) are combinations of channel reservation, handoff queueing, channel transferred, genetic and subRating schemes ([75]-[85]). The key idea is to combine the different prioritization policies in order to further decrease the blocking probabilities or to improve the channel utilization. Table VI summarizes the policies that each scheme adopts.

In [67], a combination of Channel Borrowing, Genetic algorithm and channel Degradation schemes mechanisms is proposed (CBGD). More specifically, the channel borrowing is realized based on an algorithm that utilizes genetic algorithms to optimize the network resources, while maintaining the quality of service requirements of the users. The algorithm is also adaptive in the sense that it re-allocates the channels allocated to different cells based upon the dynamic traffic pattern demands from the users. The simulation results showed that by applying this scheme the network efficiency is increased, as more calls can be accepted for the same amount of resources at a certain call blocking probability, and that the channel borrowing algorithm enhances the QoS level offered to the calls. More specifically, the average percentage of QoS enhancement is 3.82%. However, the author mentioned that when the offered traffic load is below 40%, there is no need for using the channel borrowing algorithm as there are enough channels in the system to satisfy at least the minimum QoS levels of the existing calls.

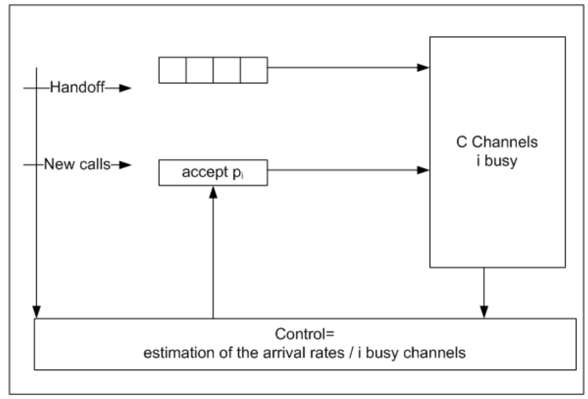

Fig. 7. The State-dependent rejection scheme (redrawn from [75]).

The State-dependent Rejection Scheme (SRS), proposed by Barcelo [75], is similar to the FGCS and the DCRS. The main difference is that both mentioned schemes are queueless, while SRS includes a queue for handoffs. The advantages of the SRS are: its applicability to scenarios that are used in theoretical analyses or simulations (e.g., non-Poisson arrivals, radio path, non-balanced cell layouts, etc.) and the capability to achieve different tradeoff degrees between the probability of blocking a new call and interrupting an ongoing one, through very simple settings. The system model of the State-dependent Rejection Scheme is depicted in Figure 7. More specifically, the authors assumed that there are C-channels available per cell. Handoff arrivals are accepted or, if necessary, placed in a queue until a channel is released. New calls are rejected if all channels are busy, and accepted or rejected with a certain probability, if there are free channels. The control block dynamically sets this probability based on the number of busy channels upon arrival and the estimation of the arrival rates (i.e., for new calls and handoffs). The algorithm needs the knowledge of the number of busy channels (i) and the function rand(), which provides a uniformly distributed random variable between zero and one.

A Queueing Priority Channel Reservation Scheme (QPCRS) for integrated real-time and non-real-time service wireless mobile networks, based on the complete sharing policy is proposed in [76]. To decrease the blocking handoff probabilities, two separate queues (one for the handoff request calls of each service class) are considered. Moreover, since real-time handoff calls have higher priority over non-real-time handoff calls and the handoff calls have higher priority over originating calls, different thresholds, based on the static channel reservation policy, are set. Analytical and simulation results showed that the forced termination and the blocking probability of originating calls are decreased. Moreover, the authors proved that if the real-time handoff calls have the ability to preempt the non-real-time handoff calls the forced termination probability can be further decreased by one order of magnitude.

Another Priority Channel Reservation (PCR) scheme for integrated Real-time and Non-real-time service wireless mobile networks (PCRRNR), based on the complete partitioning policy, is proposed in [77]. More specifically, the authors consider two queues, one for real-time handoff requests and another one for non-real-time handoff requests. For QoS provision of these two different service calls the scheme also adopts the channel reservation partitioning policy. Therefore, different thresholds for real-time and non-real-time handoff and originating thresholds are considered. Simulation, with both exponential and gamma distribution scenarios, are also obtained and results are observed to match with the analytical evaluations. From these results, it was shown that forced termination probability of handoff request calls of real-time service mobile users can be decreased by proposed preemptive and priority reservation handoff schemes with 31% more decrease for the preemptive policy. Moreover, the authors showed that non-real-time service handoff requests do not fail, except for negligibly small blocking probability, as a non-real-time service handoff request can be effectively handled by transferring it from the queue of the reference cell to an adjacent cell.

A queueing priority channel reservation scheme, the CPCPCB that combines the channel reservation partitioning policy and the channel borrowing policy is proposed in [78]. More specifically, in this scheme the available bandwidth of each cell is distinguished into two sub-pools, one for real-time calls and the other one for non-real-time calls. The authors, also, consider two queues, one for real-time handoff requests and the other for non-real-time handoff requests. Moreover, in order to increase the channel utilization, real-time service handoff requests are allowed to borrow channels from the non-real-time sub-pool, only if there are idle channels in the non-real-time sub-pool. The simulation and analytical results for the preemptive and non-preemptive policies showed that in both cases the resource utilization is improved and are close to the CS policy (the difference is less than 6%). Also, the results showed that the preemptive policy performs better than the non-preemptive at the cost of slightly increased handoffs for non-real-time service calls. However, the effectiveness of the schemes depends on the control of the channels borrowing.

In [79], a combination of a Cut-Off and a Channel Carrying (COCC) policy is presented. More specifically, a number of channels are reserved exclusively for handoff calls. However, if there is no available channel for an arriving handoff request call, the subscriber is allowed to carry its currently occupying channel to the destination. Simulation results showed that the proposed scheme offers higher channel utilization, as well as, a lower handoff blocking ratio than the guard scheme and the channel carrying scheme under all traffic loads.

A more general handoff priority scheme, the General Channel Allocation Scheme (GCAS) that combines the idea of a guard channel, static queueing and the SubRating scheme is presented in [80]. By applying these different policies the GCAS inherits all the advantages of them. However, due to the complexity of the operational structure of the channel allocation scheme, it may be too difficult to achieve analytically formulas under more general assumptions for the cell traffic and holding time distributions.

In [81], a Non-Preemptive Priority Handoff queueing (NPPH) scheme for a multi-traffic wireless network is proposed that supports three types of traffic; type 1: for real-time applications (e.g. voice, video), type 2: for semi real-time applications (e.g. www browsing) and type 3: for non-real-time applications (e.g. file downloading, email). The system model of this scheme is depicted in Figure 8. Due to the prioritization of handoff calls and the differentiation of types of traffic simulation and analytical results show that the forced termination probability of sensitive delay type-1 calls is six orders lower than the blocking probability of originating calls. An extension of this scheme is proposed in [82], where handoff request calls, with higher priority, may preempt other handoff request calls with lower priority. The simulation and the analytical results showed that the preemption of handoff request calls with lower priority decrease further by one order of magnitude the forced termination probability of the highest priority handoff call.

Also, in [83] Wu *et al*. presented a hybrid handoff scheme; the Predictive Channel Reservation with Channel Borrowing (PCR_CB). This scheme combines the predictive PCRS [52] and dynamic channel borrowing among cells in time of congestion, in order to provide services to handoff requests with higher priority over new call requests. Simulation results showed that the use of the channel borrowing approach further improves the performance of the PCRS by reducing the handoff blocking probabilities. In addition, the authors in [84] present the CDMA-SubRating scheme (DCMAS), which combines the sub-rating approach and the handoff queueing approach. More specifically, the idea is to serve the handoff calls by subrating the existing connections if there are no channels available on arrival. If all the sub-channels are sub-rated on arrival, the handoff calls will be placed in a queue, while the MTs are in the handoff area. Numerical and analytical results showed that subrating is beneficial for the CDMA networks, due to the fact that the soft handoff mechanism needs more channels than the hard handoff one. The main drawback of this scheme is the degradation of the voice quality, due to subrating.

Finally, the authors in [85] present a static reservation handoff queueing scheme, the Priority Based Intercell Handoff Scheme (PBIHS) that takes into account the high-speed users. In this scheme the authors consider three queues, for voice handoff requests, for data handoff requests and for originating call requests. Calls coming into the system are passed first through their respective queues. According to the call type, different thresholds have been set, so that the priority of data handoff request is higher than call originating call, but lower than voice handoff request. Also, a handoff request from a high speed user has higher priority than a slowly-moving user. Moreover, in order to prevent the starvation of calls with lower priority, a preemptive scheme is also presented. The idea is to assign priority values to incoming calls which are increasing during their waiting to be served. If their priority value exceeds the priority value of any type of call served by a channel then it preempts that call with the lower priority value. Simulation results showed that in a busy area, where the mobile users rapidly change their locations the preemption policy is always the best choice.

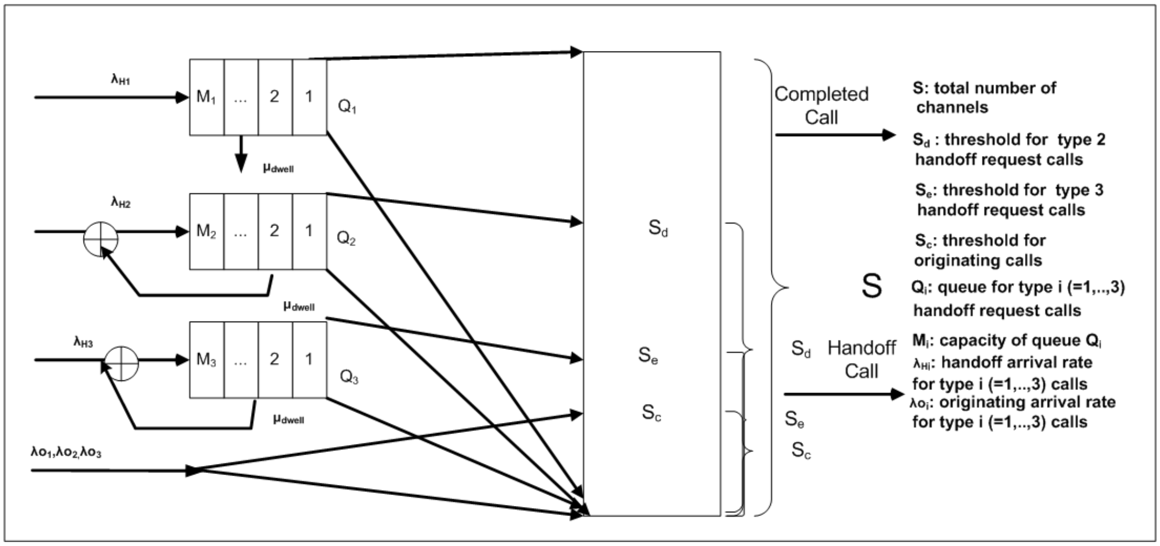

Fig. 8. The system model

TABLE VI
HYBRID SCHEMES CHARASTERISTICS

Reference	Channel Reservation	Queuing	Channel Transferred	Subrating	Genetic
SRS	Dynamic	Static			
QPCRS	Static	Static			
PCRRNR	Static	Static			
CPCPCB	Static		Channel Borrowing		
COCC	Static		Channel Carrying		
CBCD			Channel Borrowing	Channel Degradation	Genetic
GCAS	Static	Static		Subrating	
NPPH	Static	Static			
PCR_CB	Dynamic		Channel Borrowing		
DCMASR	Static			Subrating	
PBIHS	Static	Static			

J. Evaluation of Horizontal Handoff Schemes

The main advantage of the static reservation schemes is their simplicity because there is no need for exchange of control information between the BSs [38]. However, such schemes are not flexible to handle the changing traffic conditions, since they do not use the traffic information in the current cell and their neighboring cells, and hence, they cannot be adapted to the real-traffic conditions [39]. Also, the critical element of static schemes is how to determine the optimal number of reservation channels [40], since this number has a tremendous effect on the performance of wireless cellular networks [86]. The fact that the number of reserved channels in these schemes is an integer number, it makes the determination of the optimal solution more difficult.

Efficient usage of guard channels requires the determination of an optimum number of guard channels, the knowledge of the traffic pattern of the area, and the estimation of the channel occupancy time distributions [15]. In [41], the authors propose several optimization algorithms for single-cell and multi-cell systems, in order to provide optimal channel assignment and ensure the priority of handoff calls. However, in these algorithms only one type of traffic has been considered. In [22], the priority of handoff call requests is ensured by a cost function, in the form of a linear combination of loss probabilities of the handoff requests and the new calls. The authors also proved that the guard channel policy is optimal while using an objective cost function, where no queueing device is considered.

Dynamic channel reservation schemes have the advantage of better channel utilization, since the adjustments allow better adaptation to traffic conditions. More specifically, the FGCS schemes have also the advantage over the GCS schemes that they distribute the new calls evenly over time, and this leads to a more stable control [47], [84]. However, the local dynamic reservation schemes, in order to be adapted to the current traffic conditions, have the disadvantage of the continuing need of traffic monitoring, resulting in signal and computational overhead. Also, Iraqi and Boutaba proved in [88] that the local dynamic reservation schemes can succeed only in controlling a local parameter, like the handoff dropping probability and not an inherently global parameter, like the call dropping probability.

In the collaboration dynamic reservation schemes the estimation of traffic is more accurate and the channel utilization is better than the local dynamic reservation schemes. However, in these schemes, due to the fact that more calculations are needed in order to predict the reservations, the problem of signal and computational overhead is more intensive in comparison with the local dynamic reservation schemes [19].

In the static handoff queueing schemes, the probability of forced termination is decreased. However, a handoff call may be still dropped, because the handoff requests can only wait until the receivers threshold is reached; in the case of high demand for handoffs, handoff calls will be denied to be queued due to the limited size of the handoff queue [22]. Moreover, static handoff queueing schemes need large buffers to deal with real-time multimedia traffic.

As mentioned in [72], the static queueing may be not practically feasible for real-time multimedia services in picocellular networks, since the time interval available for queueing handoff requests might not be sufficiently long enough for bandwidth resources to become available, especially for wideband handoff calls. A sophisticated scheduling mechanism is proposed to meet the QoS requirements for delay sensitive connections and guarantees that the queued data will not expire before being served [45].

By the priority reordering in the handoff in the queue, DPQS schemes achieve the reduction of the forced termination probability in comparison with the FIFO handoff queueing schemes. However, in order to enable the system to be adapted to the new traffic situation, further information is required, which results in computational or signaling overhead [64].

The channel transferred schemes ensure that an ongoing call is not forcibly terminated due to channels unavailability. Since channels do not need to be reserved a priori, the system utilization is increased [65]. However, the major disadvantage of the schemes is that carrying a channel into a new cell or even borrowing a channel from neighboring cells, it results in an increased signaling overhead due to negotiation activities with the neighboring cell of the channel in use [64].

SubRating schemes achieve better performance in terms of call-blocking probability and forced-termination probability in saturated conditions. However, the degradation of wideband calls may reduce the QoS [72]. Finally, the genetic handoff scheme has the advantage of finding better admission policies compared with other well-known methods of handoff reservation. However, the time needed to assign channels for the GAS scheme is the main drawback of this scheme [58], [64].

TABLE VII
PRIORITIZATION SCHEMES COMPARISON

Prioritization Scheme	Advantages	Disadvantages
Static Channel Reservation	Simplicity	Inflexible to traffic change situations
Dynamic Channel Reservation	Flexible to traffic change situations	Computational and signaling overhead
Static Queueing	Easy to Implement	Difficult to accomodate multimedia traffic
Dynamic Queueing	Reflection of the dynamics of the users motion	Computational and signaling overhead
Channel Transferred	Increases system efficiency	Signaling overhead
Subrating	Increases system efficiency	QoS Degradation
Subrating	Improves channel utilization	Delay needed to assign channels
Hybrid	Improves channel utilization Decreases blocking probabilities	Difficult to find the optimal combination

IV. VERTICAL HANDOFF PROCESS

As it was previously mentioned, the notion of the vertical handoff was introduced with the appearance of the first heterogeneous networks, where an MT needs to handoff between different network technologies. However, the use of different network technologies creates new challenges in the network technologies, as well as in the handoff management, especially in the decision of when the handoff is necessary and which network technology should be selected.

In this section, we discuss several issues concerning the vertical handoff process.

A. Handoff Phases

The vertical handoff process may be distinguished in the following three phases [90], [91]:

- **System discovery:** During this phase, the MTs determine which networks can be used and the services available in each network. The networks may also advertise the supported data rates for different services and the Quality of Service (QoS) parameters.
- **Handoff decision:** During the handoff decision phase, the mobile device determines the network that should be connected to, based on several parameters, as Figure 9 depicts.
- **Handoff execution:** During the handoff execution phase, connections need to be re-routed from the existing network to the new network in a seamless manner. This phase also includes the authentication and authorization, and the transfer of user's context information.

B. Vertical Handoff Decision Algorithms

Since the decision phase is the most important phase in vertical handoffs, several algorithms, that use several different parameters, may be found in the literature (Table VIII).

The author in [92] presents the handoff decision phase in heterogeneous networks, as a fuzzy Multiple Attribute Decision Making (MADM) problem, and fuzzy logic is applied to

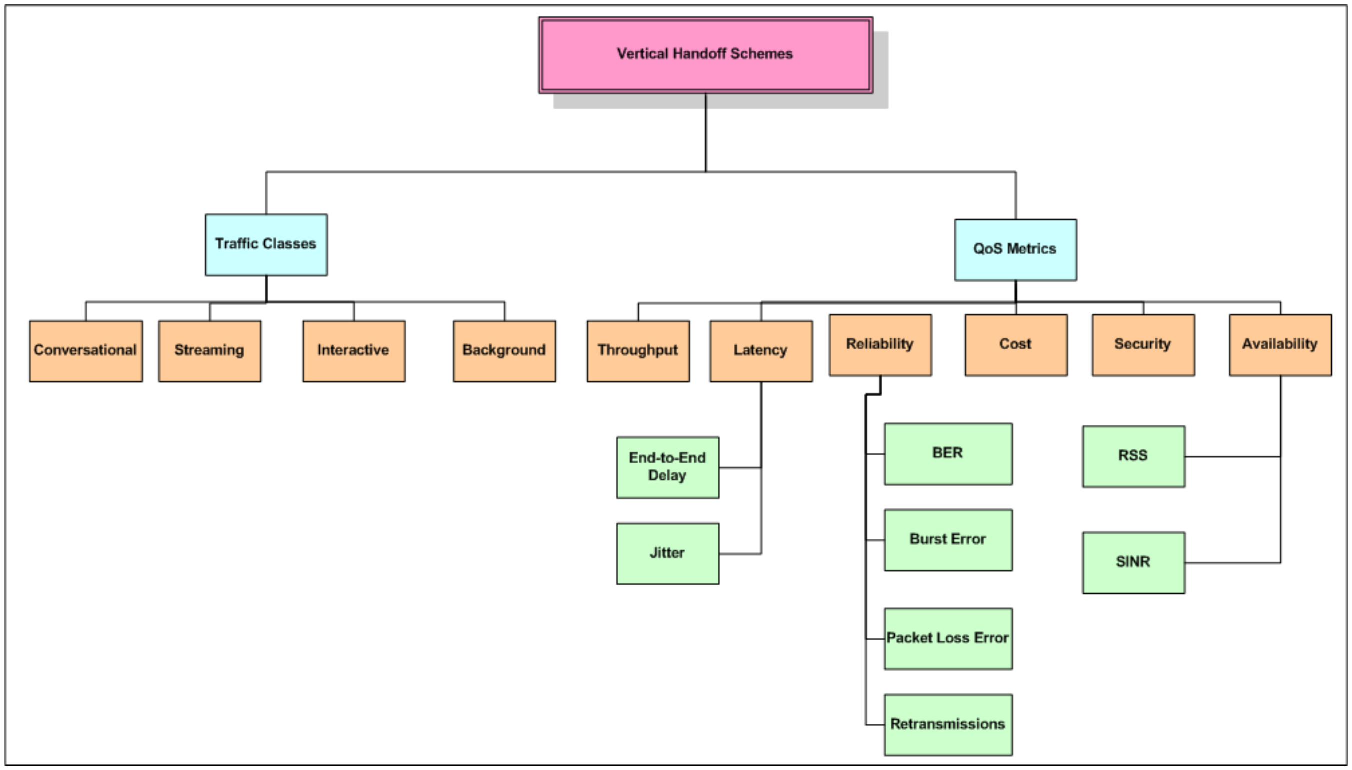

Fig. 9. Traffic Classes and Handoff Metrics

deal with the imprecise information of some criteria (price, bandwidth, SNR, sojourn time, seamlessness and battery consumption) and user preference. More specifically, in order to decide to handoff, firstly the imprecise data should be converted to crisp numbers, and then, classical MADM should be applied in order to rank the two networks. The authors consider two different MADM methods: the SAW (Simple Additive Weighting) method and the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method. Numerical analysis showed that TOPSIS is more sensitive to user preference and attribute values, while SAW gives a relative conservative ranking result.

Also, the authors in [93] integrate the Analytic Hierarchy Process (AHP) and the Grey Relational Analysis (GRA) into the network selection algorithm in order to select the best network (Universal Mobile Telecommunications System (UMTS) or Wireless Local Area Network (WLAN)) for the mobile users. More specifically, the AHP is used to weight the decision factors (i.e. throughput, delay, response time, and jitter, BER, burst error, average number of retransmissions per packet, and packet loss ratio, security, cost, received signal strength (RSS) and coverage area) and the GRE to prioritize the networks. The simulation results revealed that the proposed mechanism can not only work efficiently for a UMTS/WLAN system but also reduces the complexity of implementation significantly. A comparison of the TOPSIS, SAW and GRA for the following attributes (bandwidth, delay, jitter and BER) can be found in [90]. Results showed that SAW and TOPSIS provide similar performance to different traffic classes and that GRA provides a slightly higher bandwidth and lower delay for interactive and background traffic classes. The results also showed that all the three algorithms select the same network between 72%-87% of time.

A vertical handoff decision strategy in overlay networks, named CVHDS (Cost-Function-Based Vertical Handoff Decision Strategy) is proposed in [4]. More specifically in CVHDS the system decides whether to handoff into a different wireless technology based on a cost function that depends on several factors, such as traffic load, received signal strength (RSS) and the Variation of Received Signal Strength (VRSS). All the factors in the cost function are normalized, making the comparison between different networks practical. Moreover, in order to avoid the "ping-pong" vertical handoff phenomenon, the authors define a threshold δ. Therefore, a vertical handoff has only to be made when the number of times that another network has the lowest cost function is larger than δ. The simulation results showed that the proposed decision strategy achieves better performance in terms of blocking probability.

The authors in [94] formulate the vertical handoff decision problem as a Markov Decision Process (MDP). The goal of the algorithm is to maximize the expected total reward of a connection. Therefore, two functions are considered: a link reward function associated with the QoS of the connection and a signaling cost function associated with the signaling overhead and the processing load when vertical handoff is performed. Numerical results showed that the MDP algorithm gives a higher expected total reward and lower expected number of vertical handoffs in comparison with the SAW and the GRA. For example, when the average connection duration is 15 min, the MDP algorithm gives 4.4% more total expected reward than the SAW and GRA policies.

The authors in [95] propose a vertical handoff decision algorithm for wireless overlay networks, called Vertical Handoff hysteresis (VHOhyst) algorithm. The handoff decision is based on the RSShysteresis in addition to the network conditions (number of active users), speed of the user, and different service types (i.e. data and voice). The simulation results showed that the proposed vertical handoff decision scheme provides acceptable QoS levels, in terms of grade of Service (GoS) and utilization by avoiding unnecessary handoffs. More specifically, simulation results showed that by applying the effect on the RSShysteresis at high mobility the number of vertical handoffs is reduced to 1/4, the system utilization remains constant and is not affected by the mobility of the users.

The Adaptive Multi-criteria Vertical HandOff (AMVHO) decision algorithm for radio heterogeneous networks (UMTS and WLAN) is presented in [96]. The AMVHO algorithm consists of a Modified Elman Neural Network (MENN) predictor and a Fuzzy Inference System (FIS). The MENN is used to do the prediction of the number-of-users and its output acts as an input of the FIS that makes the analysis of relevant criteria and does the final decision according to the inputs and the if-then rules. Simulation results showed that the AMVHO algorithm is effective in taking the accurate handoff decision. Also, in comparison with a conventional vertical handoff algorithm, that takes into account only RSS as decision parameter, the proposed algorithm achieves better performance in guaranteeing QoS, since it keeps BER and SNR in stable states and the number of dropped packets to zero.

The authors in [97] propose the QoS-based Vertical Handoff Decision algorithm (QoSVHD) for heterogeneous environments (CDMA, WLAN and WiBro, based on 802.16e). More specifically, the handoff decision is based on a utility function that takes into consideration parameters such as the Signal to Interference plus Noise Ratio (SINR), the bandwidth, the traffic load and the users mobility. A mobile user calculates the utility functions of all candidate systems periodically, and decides a target system, the utility function of which is the maximum. Also, in order to avoid the ping-pong effect, a time dweller is considered, so a user can check whether a system is “consistently better” and tends to perform a handoff slowly. Simulation results showed that the utility function effectively increases throughput.

The receiving SINR from WLAN and WCDMA networks is also used in the SINR-based Vertical Decision Handoff algorithm (SINRVDH) proposed in [98]. The performance analysis results showed that the proposed SINR based vertical handoff algorithm is able to consistently offer the end user the maximum available throughputs during vertical handoff, under any noise level and load factor, in comparison with the RSS-based vertical handoff decision algorithm, the performance of which differs under different network conditions, for different threshold settings.

Also, the authors in [99] present an Intelligent Vertical Handoff Algorithm (IVHA) based on pattern recognition for the next generation wireless networks (UMTS and WLAN). Moreover, as pattern classifier, the authors use Probabilistic Neural Networks (PNN). Simulation results indicated that PNN achieved better performance than traditional classifying algorithms and therefore, more accurate results. Also, the algorithm showed 90% reduction in ping-pong effect, 2.7% improvement in WLAN usage factor and 4 times reduction in crossover distance.

TABLE VIII
VERTICAL HANDOFF DECISION SCHEMES CRITERIA

Vertical Handoff Decision Scheme	Criteria
MADM-based	Price, bandwidth, SNR, sojourn time, seamlessness, battery consumption and user preference
Combination of AHP and GRA	Throughput, delay, response time, and jitter, BER, burst error, average number of retransmissions per packet, and packet loss ratio, security, cost, received signal strength (RSS) and coverage area
CVHDS	Traffic load, RSS and VRSS
MDP	Bandwidth, delay, switching and signaling Cost, QoS, type of Service etc
VHOhyst	RSShysteresis, number of active users, speed of the user and type of service
AMVO	Number and velocity of users, bandwidth
QoSVHD	SINR, bandwidth, traffic load and the users mobility
SINRVDH	SINR
IVHA	Speed of users, RSS
CVHDF	Monetary Cost, QoS, Power Requirements, User Preference, etc.

A vertical handoff decision algorithm for wireless heterogeneous networks (WWAN and WLAN), called Vertical Handoff Decision Function (VHDF) is proposed in [100]. More specifically, the VHDF enables devices to assign weights to different network factors such as monetary cost, quality of service, power requirements, personal preference, etc. The proposed algorithm significantly advances the system flexibility and extensibility and provides more accurate handoff decisions at any given time.

C. Vertical Handoff Solutions

As stated in [101], the various vertical handoff solutions that may be found in the literature can be classified into the network-layer approaches and the upper-layer approaches (Figure 10).

1) Network Layer Vertical Handoff Solutions: Network layer approaches are typically based on IPv6 or Mobile IPv4 standards, requiring the deployment of agents on the Internet for relaying and/or redirecting the data to the MT [101].

Also, a mobility management system for vertical handoff between a WWAN and a WLAN network, based on Mobile-IP is proposed in [102]. The system consists of two different components; the Connection Manager (CM) that intelligently detects the wireless network changes based on MAC sensing, the FFT detection and adaptive threshold configuration and the Virtual Connectivity manager (VC) that maintains connectivity using the end-to-end principle. Simulation results showed that collaboration between the CM and VC accomplishes seamless handoff between WWANs and WLANs and that by using this approach the throughput of the system is much higher (over 50%) in comparison with the traditional Mobile-IP approach.

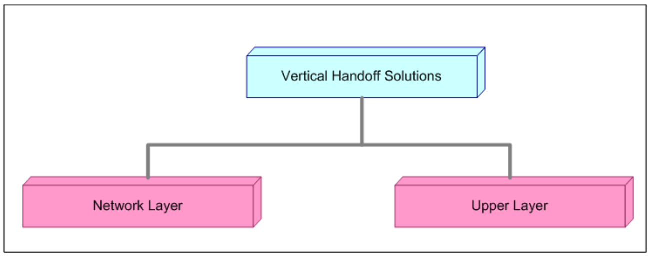

Fig. 10. The Vertical Handoff Solutions Classification

The authors in [103] propose a network handoff vertical solution in an integrated WWAN and WLAN network, based on Mobile-IP that intends to minimize vertical handoff delay and to decrease packet loss rate during vertical handoffs. This is achieved by separating the vertical handoff procedure in two steps: the Pre-handoff and Handoff that are allowed to run in parallel. This approach is implemented by considering two modules: the Decision Module and the Action Module. The Decision Module detects the network condition and by using the predictive handoff action time and a pre-set expected pre-handoff time can trigger the Action Module to start to set up multiple tunnels (Pre-handoff action) in advance to the handoff execution phase. Simulations showed that the delay of the proposed scheme is much lower than that of the traditional Mobile IP approach and is related to the expected time duration between the Pre-handoff and Handoff decision. However, as the authors stated, this approach presents two limitations:

1) The multi-tunneling technique introduces additional resource consumption of the wireless link.
2) Since both air interfaces are used, during the Pre-handoff action, the power consumption is increased.

The authors in [104] propose a vertical handoff decision strategy in an integrated 3G-WLAN network, called Wise Interface Selection (WISE) in order to minimize the energy consumption in the mobile terminals, without degrading the throughput. This is achieved by allowing the MT to select the transmitting and receiving links that have the lowest power consumption from available networks. More specifically, the key idea is to let the MT to select the WLAN network interface when it has a large amount of data to send or receive and the 3G network interface for small amounts of data. Simulation results showed that WISE reduces the power consumption without degrading the throughput. However, although this strategy achieves less power consumption, the system is complex, since the mobile user may use transmitting and receiving links from different networks simultaneously [4].

A survey concerning vertical handoff solutions for integrated WLAN/Cellular at the network layer can be found in [105].

2) Upper Layer Vertical Handoff Solutions: The uppermost upper layer approaches implement a session layer above transport, making connection changes at underlying layers transparent to the application.

Other upper layer approaches suggest new transport layer protocols or modifications to existing transport layer protocols to provide necessary handoff support [101].

For example, the authors in [106] proposed a TCP scheme that can quickly estimate available bandwidth during soft vertical handoff. Then, TCP updates the adaptive slow-start threshold (ssthresh) and congestion window size (cwnd), in the new network. From the obtained simulation results, applied in a 3G-WLAN, it was shown that, by freezing the TCP transmission during a handoff, it prevents packet drops and a backed-off Retransmission TimeOut (RTO) value during the handoff.

Also, a vertical handoff scheme, named VHOST (Vertical Hand-Off through Seamless TCP-migration) for heterogeneous networks is proposed in [107]. The VHOST architecture consists of three modules: the migration monitor module, the handoff-aware TCP core module and the resumption module. More specifically, the migration monitor module monitors all network statuses from all network interfaces and, if an ongoing vertical handoff is detected, it activates the connection migration procedure to migrate all current TCP connections from the old network to the new one. The resumption module provides an interface to migration monitor for obtaining information about suspensible TCP connections and for triggering connection migration. The handoff-aware TCP core performs two tasks: to migrate the current connection from a network interface to another one, and to agilely adapt the migrated TCP connection to the new network characteristics. Experimental results in an overlay Ethernet-802.11 WLAN-GPRS network showed that TCP performance can be improved by applying the VHOST scheme and that the handoff time between the different networks is acceptable.

In addition, in [108], a vertical handoff solution in a WLAN/UMTS network, based on the mobile extension of the Stream Control Transmission Protocol [109], called (mSCTP), is proposed. The mSCTP is able to add, delete, and change the IP addresses dynamically during an active SCTP association, and thus providing an end-to-end UMTS/WLAN vertical handoff solution. Therefore, since no addition or modification of network components is required, the proposed scheme has a network architecture that is much simpler than those required by network layer or application layer solutions. Simulation results showed that delay and throughput performance can be improved significantly using the dual-homing configuration with message bundling.

A transport vertical handoff solution is also presented in [110], called cellular SCTP (cSCTP) that utilizes the dynamic address reconfiguration extension of SCTP. More specifically, cSCTP provides smoother handoffs by sending duplicate data to a hosts addresses on both the old and new networks during a transition and also lowers the potential for loss [111]. It also uses the mobility management functionality of SIP to enable seamless handoff [112]. A survey concerning vertical handoff solutions at the transport layer can be found in [113].

V. Conclusions

Handoff in a homogeneous network (or handover or Automatic Link Transfer (ALT)) is the process of changing the channel (frequency, time slot, spreading code, or combinations of them) associated with the current connection, while a call is in progress. Handoff failure will result in the forced termination of an ongoing call. Therefore, the service of quality of wireless mobile networks depends on the handoff strategy. As a consequence, since the handoff process is managed by the so-called handoff schemes, the main interest is focused on them.

In order to support the different services and the different traffic requirements in homogeneous networks, several handoff schemes have been proposed. These schemes are classified into categories based on the policies they adopt in order to ensure the prioritization of the handoff calls. More specifically, channel reservation schemes reserve channels exclusively for handoff requests, while queueing schemes pose the handoff request calls into queues instead of denying their service. Channel transferred schemes allow the transfer of a channel from a neighboring cell to accommodate the handoff request call while the SubRating schemes degrade the bandwidth of an existing call in order to accept more handoff calls. Finally, genetic schemes use genetic algorithms to apply the local policies while hybrid schemes try to combine the policies of channel reservation, handoff queueing, channel transferred, genetic and SubRating schemes in order to give priority to the handoff request calls.

The application of each scheme in a wireless cellular network has its advantages and disadvantages, as Table VII depicts. Therefore, further investigation in order to develop a hybrid scheme that will support the different services and the different traffic requirements of the wireless network is needed in order to improve the performance of a network.

With the penetration of next generation wireless mobile networks and personal communication systems and the exploitation of the micro cell and hybrid cell (macro-, micro-, pico-) architectures a new type of handoff has been occurred, the vertical handoff. Vertical handoff is the process of changing the mobile active connection between different wireless technologies. However, since these technologies present different characteristics in terms of coverage, bandwidth and delay, handoff is a critical process and should be taken under careful consideration in order to ensure the continuity of connections and the QoS perceived by users.

In this paper, we provided a comprehensive survey of the basic elements and the different types and phases of the handoff procedure. Particular interest has been given to the horizontal handoff execution phase by classifying the most recent handoff prioritization schemes into categories in the vertical handoff decision phase by presenting different decision algorithms.

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