A Survey on Handoffs – Lessons for 60 GHz Based Wireless Systems

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***Abstract*—Wireless communication is playing an important role in our daily life since it offers flexibility and mobility. New multimedia services demand data-rates of up to hundreds of Mbps and thus higher frequency bands are being explored to support these new high data rate services. However, to support mobility, handoff is a must in many of these networks and systems. In the mean time the 60 GHz band has received much attention due to its 5 GHz of the available spectrum globally. However, the 60 GHz channels face many challenges such as high attenuation and NLOS propagation. The high reduction in signal strength as a function of distance results in a small coverage area, thereby causing frequent handoffs for mobile terminals. In this paper, we discuss and compare handoff algorithms intended for WLAN, GSM, UMTS, etc. We study these algorithms from the point of view of their usability in 60 GHz networks and make recommendations for handoff algorithms in such networks.**

***Index Terms*—60 GHz, handoff procedure, handoff issues.**

I. INTRODUCTION

WIRELESS communication play an important role in the modern world because of its mobility and flexibility with more than 3.2 billion users now and a hundredfold increase of traffic expected by the year 2013 [1]. In the future, the home and office networking environments are predicted to be dominated by a variety of multimedia services like wireless HDTV, wireless home entertainment and virtual wireless office [2]. In order to support these applications, the wireless network should provide the user with transmission capacity of hundreds of Mbps using short-range Gbps wireless technology and using techniques like antenna diversity, sophisticated coding schemes, etc. With 5 GHz of unlicensed spectrum available at 60 GHz band, it is an obvious candidate for the PHY layer of future home networks.

Handoff is an important aspect in wireless and cellular communication due to the mobility of devices. It is the process that allows a user to move around while keeping an ongoing call or session on a terminal. It does so by changing its current channel in the current cell to a new channel in either the same cell or in a different cell [3]. Handoff is usually transparent to the user, but it directly affects the quality of service. A lot of research has been done on handoffs in cellular networks and WLAN. However, little work has been done on handoff in 60 GHz systems. Two types of handoffs are distinguished: horizontal handoff and vertical handoff. Horizontal handoff occurs when a mobile station (MS) is moving out of the coverage of a base station (BS) into the coverage of another BS within the same system. Vertical handoff is defined as handoff between BSs that use different wireless networking technologies, e.g., WLAN to and from cellular wireless networks.

This paper introduces the currently used handoff algorithms and discusses handoff issues in the 60 GHz band. Before we address the 60 GHz-specific issues, we compare the handoff algorithms that are proposed and implemented in the wireless and cellular systems. The paper is organized as follows: first, in Section II we explain the characteristics of the 60 GHz band. In Section III, we present handoffs in current wireless technologies, handoff-related resource management and the handoff issues in 60 GHz-based systems. In Section IV, handoff algorithms and their comparison are discussed. Section V discusses vertical handoffs. We discuss the handoffs in 60 GHz radio in Section VI and conclude in Section VII.

II. 60 GHZ-BASED WIRELESS SYSTEMS

The 60 GHz millimeter wave band is a candidate for the short-range Gbps wireless systems to satisfy the future bandwidth hungry applications. With a huge spectrum of 5 GHz allocated for unlicensed use, the 60 GHz band has become very attractive for future indoor networking. It has already received a lot of attention in [4]–[10]. The main advantage of the 60 GHz band has been discussed in [9]. Foremost of them are, large spectrum availability, reuse of frequencies, and high data rate which can be achieved. Further more, the small size of antennas and RF circuits, allows the integration of 60 GHz technology in small devices.

On the other hand, due to the limits imposed on the emitted power, the high temperature noise, and the high oxygen absorption, the range of 60 GHz system is short. The propagation of 60 GHz signal is easily obstructed by the movement of people, and the presence of furniture and walls. This however opens up the opportunity for spatial reuse of channels. Channels in the indoor or open areas show a strong multipath behavior because of easy reflection. So 60 GHz is usually envisaged for communication confined to a room or an open area where LOS signals from the antennas can be expected. In Fig. 1, the comparison of the coverage between the 60 GHz band and the 2.4 GHz band has been illustrated using the measured data. The 2.4 GHz system requires only three antennas or access points (AP) to cover the whole building while for the 60 GHz band we need at least one antenna per room. In [4] it is shown that the SNR can drop from 20 dB to 0 dB within a few centimeters in the indoor environment (Fig. 2).

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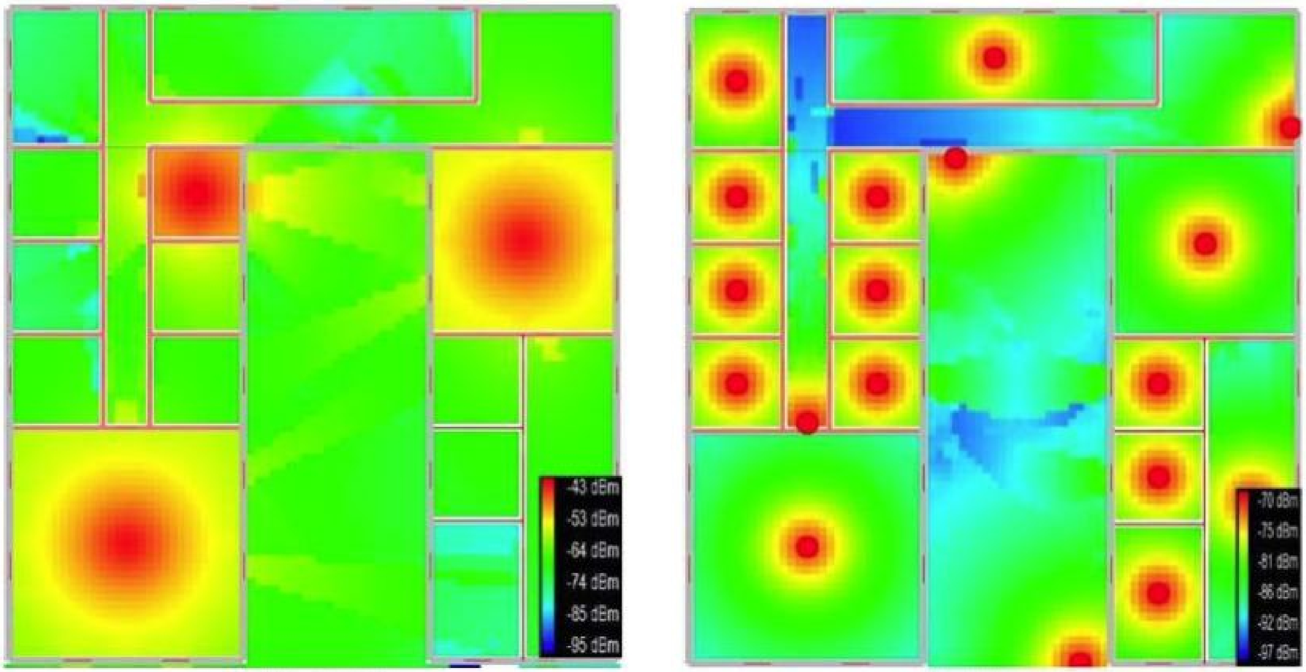


(a) 2.4 GHz (b) 60 GHz

Fig. 1. The coverage of 60 GHz compared with that of 2.4 GHz in the same building

TABLE I
A COMPARISON OF THE 60 GHZ BAND WITH OTHER BANDS [9]

Technology \ Features	Spectrum available	Channel bandwidth	Max possible Data Rate	Global Availability
60 GHz	5 GHz	2500 MHz	25000 Mb/s	Y
802.11n	0.67 GHz	40 MHz	1100 Mb/s	Y
UWB	1.5 GHz	520 MHz	80 Mb/s	N

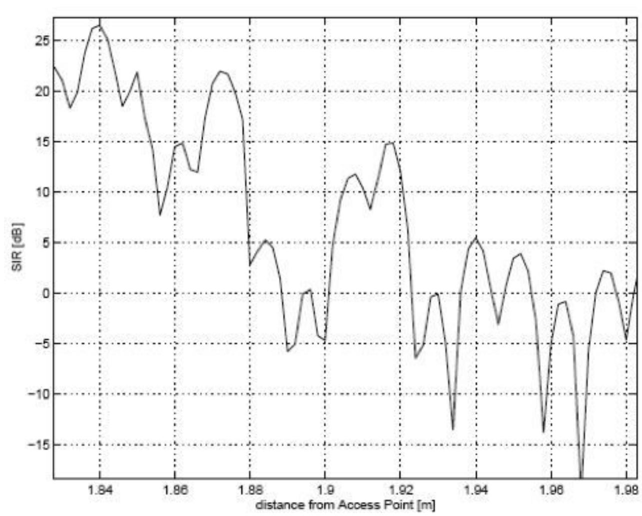


Fig. 2. The variant SIR along the hallway path [4]

Table I shows a comparison of 60 GHz technology with other high frequency wireless technologies in terms of available spectrum, channel bandwidth, maximum data rate and global availability.

Applications that might benefit from the advantages of 60 GHz are summarized in [5], we mention them briefly here:

- Broadband wireless network for indoor environments: The pico-cell structure of the 60 GHz band is easily applied to indoor applications within a large building [2], [11].
- Vehicle-to-highway communication: The use of millimeter waves also appears to be convenient for inter-vehicle or vehicle-to-fixed-infrastructure communication [12].
- Railway Communication: In a modern railway transportation system, not only efficient communication between railway traffic control and the trains in the network is vital, but also the communication needs of the passengers with the external world is important. For instance, the passengers should be able to access broadband Internet [13].
- Aircraft communication: An in-flight entertainment system for passenger aircraft requires a total data rate of the order of several Gbps with user densities of up to one thousand passengers per system. A well designed 60 GHz WLAN system is very appropriate for in-flight entertainment [10].
- Inter-satellite links: The use of the 60 GHz band for

inter-satellite links has been investigated by NASA and presented in [14]. Since satellite is totally outside the atmosphere, signals are subject to only free-space propagation loss. The proposed application uses the 60 GHz band for transmission between two or more satellites to relay signals from two stations on earth which are too far to be served by only one satellite.

III. Handoff in GSM, UMTS, WLAN, LTE, Mobile WiMAX and 60 GHz-based Systems

A. General

Handoff is a process which maintains continuity of a call or a session of a mobile station (MS) while moving in and out of the coverage area of different cells. It does so by changing the current channel in the current cell into a new channel when the MS moves into a new cell [3]. Fig. 3 illustrates a handoff scenario, in which a MS is connected to a base station (BS), BS_1. It moves from BS_1 to BS_2 while in a call. Handoff will be performed in the overlapping area between two BSs where the MS can receive the signal from two BSs. The signal strengths from BS_1 and BS_2 are measured continuously. If the signal strength of BS_2 is better than the one of BS_1 and it can provide the MS with the required resources, a handoff decision is made and now the MS is connected to BS_2.

In case, the new BS can not support the required resources of the connection, the handoff is denied and the connection is dropped. The call dropping probability (CDP) is the possibility of a connection being forced to terminate due to the lack of resources in the target BS. If a new connection access to the target BS is denied, it is called as blocked connection. The call blocking probability (CBP) is the possibility of a new connection being denied admission into the network. The CDP and the CBP are two fundamental QoS parameters in cellular wireless networks. They offer a good indication of a network's QoS in terms of mobility. Another important QoS parameter is bandwidth (channel) utilization or an effective use of bandwidth in a network.

In general, a handoff procedure has three phases: the first phase is the measurement. The result of this phase is the measurement report with measurement criteria used; the second phase is handoff decision, this is usually performed by handoff algorithms with algorithm parameters and handoff criteria as inputs; and the third phase is the execution in which the new channel will be assigned to the MS and the old connection will be terminated with handoff signaling and radio resource allocation [3].

In the handoff decision phase, if the network makes a handoff decision based on the measurement of the MSs at a number of BSs, it is called Network Controlled Handoff (NCHO). In case the MS makes measurements and the network makes the handoff decision, it is called Mobile Assisted Handoff (MAHO). When each MS completely controls the handoff process, it is Mobile Controlled Handoff (MCHO).

From the point of view of a connection, handoffs can be divided into two classes: hard handoff - where the existing connection is broken before making a new one; and soft handoff - where both the existing connection and the new connections are used while the handoff takes place:

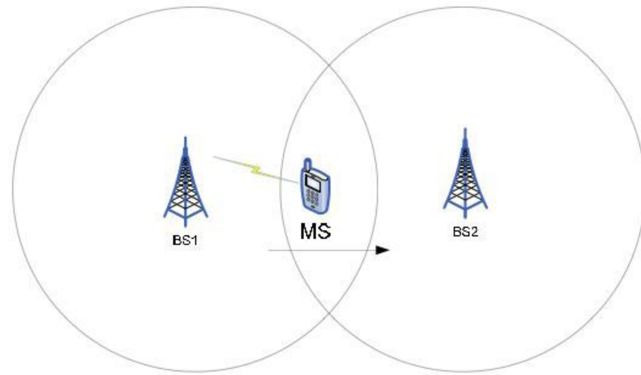


Fig. 3. Handoff in wireless networks

- The hard handoff that occurs in the current cell is called intra-cell handoff, and the hard handoff that occurs when a MS moves into another cell is called inter-cell handoff. This hard handoff is usually used in FDMA and TDMA where the MS can be connected with at most one base station at a time.
- One can distinguish between two types of soft handoffs: multi-way soft handoff and the so-called softer handoff, when two BSs exist in two sectors of a sectorized cell [15].

In principle, soft handoff can be used with any radio technology. However, the cost may be high and the support for soft handoff may not be good for particular technologies. This is the reason that soft handoff is commonly used only in CDMA. We will not discuss it further in this paper.

B. Handoff Requirements

Handoff may affect many aspects of wireless networks such as, quality-of-service (QoS) and the capacity of the network. So there are a number of desirable features and requirements to reduce the adverse effects of a handoff:

- The latency of the handoff must be low. The handoff should be fast enough so that the user cannot detect any degradation of service or interruption during a handoff.
- Given a particular trajectory of a MS, the total number of handoffs should be minimal while the ratio of successful handoffs to total attempted handoffs should be maximized.
- The effect of handoff on QoS should be minimal. For example: the probability of new call blocking and dropping a current call should be minimized, and the traffic between the adjacent cells should be balanced.
- The additional signaling during the handoff process should be minimized.

In order to achieve the desired features of handoffs, the designers must take into account the factors that affect the handoff process. Let us discuss them here:

- Wireless technology: The wireless technology used in the wireless network also decides the cell size and cell topology and the traffic model. Nowadays networks may employ multiple wireless technologies simultaneously such as: Bluetooth, WLAN, GSM and UMTS. This leads to a new requirement of handoff procedures between two different wireless technologies; this is called vertical handoff.

- Cellular structure: The cellular structure determines the handoff due to cell size. There are five types of cells ordered by size: umbrella cell, macro-cell, micro-cell, pico-cell, and femto-cell. When the cell size decreases, for a given MS mobility scenario, handoff is more frequent and the time constraint will also be more stringent.
- Topographical features: Topography is an important element of the design of a wireless network. Part of this is the selection of the antenna locations. This together with the trajectories of the users' movement determines the performance of the handoff.
- Mobility: The speed and direction of the user also affects the handoff. When the user moves fast, time for handoff is shorter and hence the handoff algorithms should deal with this requirement.
- QoS: Whenever the QoS decreases such as the BER, bandwidth or packet loss, the handoff may be requested to connect with another BS that can guarantee the QoS.

C. Handoff and Resource Management

Resources in wireless networks are frequency channels, timeslots, code channels; transmission power, battery energy; the number of transceivers. A good management of radio resources can help service provider in saving cost and increasing revenue; increasing quality of service and the effectiveness and efficiency of wireless networks. Resource management can help handoff in wireless networks in reducing handoff drop probability and keeping QoS during and after the handoff. In case of a handoff resource shortage, it is impossible to maintain the QoS parameters (for example, a required bandwidth is not negotiated) and the call can be disconnected after the handoff. Some issues of the resource management related handoffs include admission control, bandwidth reservation, and power control (Fig. 4).

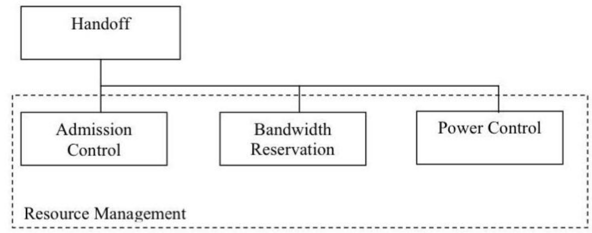


Fig. 4. Handoff-related resource management

In admission control, new calls and ongoing calls can be treated differently. It helps to keep the system from being overloaded. New calls may be queued and handoffs may be prioritized. Information required for admission control are: requirements from users and applications; the conditions of physical channel; MAC protocol and scheduling policy; the mobility of user. So admission control must challenge with: the end-to-end QoS in multi-hop network or interconnected network; random traffic: random arrival packet process, connection duration; and random user movement. Admission control policies can be done in either centralized or distributed fashion.

The bandwidth in a wireless network may be the most precious and important resource. When a bandwidth reservation is done or when a channel is available, a handoff request can be carried out. A simple solution is that each cell should reserve fractional bandwidths of its capacity and this reserved bandwidth should be used only for handoffs and not for the new call requests. However, the open question is to find how much bandwidth is sufficient while the network also maintains the maximum bandwidth utilization and keeps the maximum rate of unsuccessful incoming handoffs below the acceptance level. Numerous schemes have been proposed to dynamically manage the allocation of bandwidth resources such as Complete Sharing: all traffic classes share the entire bandwidth, Complete Partitioning: bandwidth is divided into distinct portions with each portion corresponding to a particular traffic class [16].

Power control is a necessary mechanism in all mobile systems because of an important role in spectrum and resource allocation as well as the battery life and safety reasons. Without interference, high transmission power achieves high SINR (lower BER and high transmission rate). Power control schemes can be used to achieve the required CIR level (Carrier-Interference Ratio). They try to reduce the overall CIR in the system by measuring the received power and increasing or decreasing the transmitted power in order to maximize the minimum CIR in a given channel allocation of the system. This helps in increasing the capacity of the network in terms of the number of mobile terminals that can be supported. Power control can be done in either centralized or in a distributed way. The power used in SIR based handoff algorithms has been proposed in [17], [18]. The power is also a parameter of the input measurements that helps in carrying out handoff decision especially in vertical handoff of UMTS with other systems.

D. Handoff Schemes

As discussed before, resource management is a good solution to reduce handoff drops. Another possible mechanism is using handoff schemes. The handoff schemes can be distinguished into Non-Prioritized Schemes (NPS) and Prioritized Schemes.

In non-prioritized schemes, handoff calls and new calls are served equally. They are blocked immediately if there is no available channel in the target BS. Since, no priority is given to a handoff request over a new call, the CDP is increased. Some of NPSs have been present. A Fully Shared Scheme proposed in [19] deals with a single class of traffic. All available channels in the BS are shared by handoff and new calls. This scheme results in high channel utilization. The Complete Sharing (CS) and Complete Partitioning (CP) policies are proposed in [20]–[22]. The CS allows all users accessing equally into the available channels all the time. Meanwhile, the CP divides the available bandwidth into sub-pools based on user types. This policy can lead to waste capacity if the load offered by a traffic stream drops below its allocated capacity. The CP can be divided into two classes: dynamic partition boundaries and static partition boundaries.

On the other hand, prioritized schemes ought to minimize both the CDP and CBP by giving the priority to handoff calls over new calls in some way. However, both requirements can not satisfy simultaneously, thus tradeoffs between them should be carried out. Non-prioritized handoff schemes perform well in terms of CBP comparing to prioritized handoff schemes. Most handoff prioritization schemes have the same mechanism: lowering the CDP while increasing CBP due to the users' QoS perspective, the user would rather being denied a new call than terminating of his ongoing call. Therefore, several handoff prioritization schemes have been proposed until now. They can be classify by two concepts [16]: i) handoff prioritization by handoff queuing and ii) handoff prioritization by reservation scheme.

In handoff queuing, handoff requests are queued and delayed until there are sufficient available resources in the target BS. If there are queued handoff requests, no new calls are permitted. Thus handoff requests receive the higher priorities than new calls. These schemes can delay the handoff process. So handoff queuing is suitable for mobile networks with large cells and large overlapping or low-speed mobile users. In future mobile networks with smaller cells such as 60 GHz network, the queue time is very short and handoff queuing is limited in such networks. [23] shows that handoff queuing can be applicable for vertical handoffs from a small cell mobile networks to a large cell mobile networks.

On the other hand, the prioritized handoff schemes based on reservation schemes (known as early blocking schemes [16]) will reserve handoff resources, admission control to be used for handoff requests. New calls can not be allocated in those reserved resources. Thus these schemes trade a lower possibility of CDP for a higher value of CBP. These schemes reuse some components of the QoS control plane such as admission control combined with other concepts: handoff resource reservation and mobility prediction. Two sub-types are distinguished in these scheme classes:

- Static schemes are simple since there is no mobility prediction, no signaling among BSs to reserve handoff resources. The Guard Channel Scheme also referred to as Cut-Off scheme in [24], [25] reserves a number of channels for handoff requests, the remaining channels are shared equally by new calls and handoff requests. However, networks employing static schemes can be a low resource utilization or handoff resource shortage in case of too many handoff requests or too few handoff reservation resources. Thus static schemes should be considered more while applying in microcell mobile networks.
- Dynamic schemes are more complex than static; they determine automatically handoff resources depending on the actual handoff resource demand. They need to predict the user mobility to adapt the amount of handoff resource dynamically. In [16], dynamic schemes are grouped into three: (1) local schemes require no signaling among BSs to retrieve possible handoff information and easy to deploy with low cost. Dynamic Channel Pre-Reservation Scheme [26], [27] requires a few parameters. More complex local scheme in [28] requires to adapt the amount of handoff resources every two hours with manual configuration of designed parameters. However, local schemes are suitable for networks with traffic pattern which do not change too quickly; (2) Collaborative per-mobile schemes can provide a higher accuracy of the estimated necessary handoff resources than static schemes and local schemes. Each mobile requires its own information storage to pre-reserve handoff resources in neighbor cells. Predictive Channel Reservation scheme [29] and Adaptive Channel Reservation [30] use GPS as a location system. Variable Reservation Scheme in [31] sums up the number of handoffs arriving from neighbor cells to determine how much resources should be reserved. It uses signal strength and speed as a location system. In small cell networks like 60 GHz, these schemes may be considered more often since there are many terminals and handoff requests; and (3) Collaborative aggregate schemes are less complex than per-mobile schemes because they use aggregated information instead of per-mobile information to pre-reserve handoff resources. [32] uses a mobility prediction to store mobility patterns in each base station in a limited-size history. To realize aggregation, the handoff resource demands of all terminals to a specific next cell are summed up and informed to the specific neighbor cell. Similarly, [33] reserves an aggregated amount of handoff resources between the neighbor cells.

The disadvantage of dynamic scheme is a need of mobility prediction to determine the unsteady amount of handoff resources accurately. GPS and RSS based systems are used but no requirements such as accuracy and precision degree of these systems are present. Moreover location systems like GPS, RSS based systems are not able to work well in unstable-signal environments such as the indoor environment. Another problem of these schemes which should be considered is the additional signaling.

E. Handoff in GSM

Analog cellular systems were introduced first in the 1980s to provide telephone services for mobile users. Many applications and the increasing QoS demands have resulted in the second generation cellular systems associated with digital speech transmission [34]. Now, the third generation of wireless communication is being introduced to accommodate broadband services. The fourth generation cellular systems are being developed. This trend makes handoffs increasingly important in wireless cellular networks. Handoff in GSM systems can be divided into four types based on the movement between Base Station Controller (BSC) and Mobile Switching Center (MSC) (Fig. 5):

- Intra-Cell handover: the MS changes the channels (time slots) in the same cell or the same base transceiver station (BTS).
- Inter-Cell handover within the same BSC: when a user travels from the current cell to another cell controlled by the same BSC.
- Intra-MSC handover: when a user travels between two cells belonging to two different BSCs controlled by the same MSC.

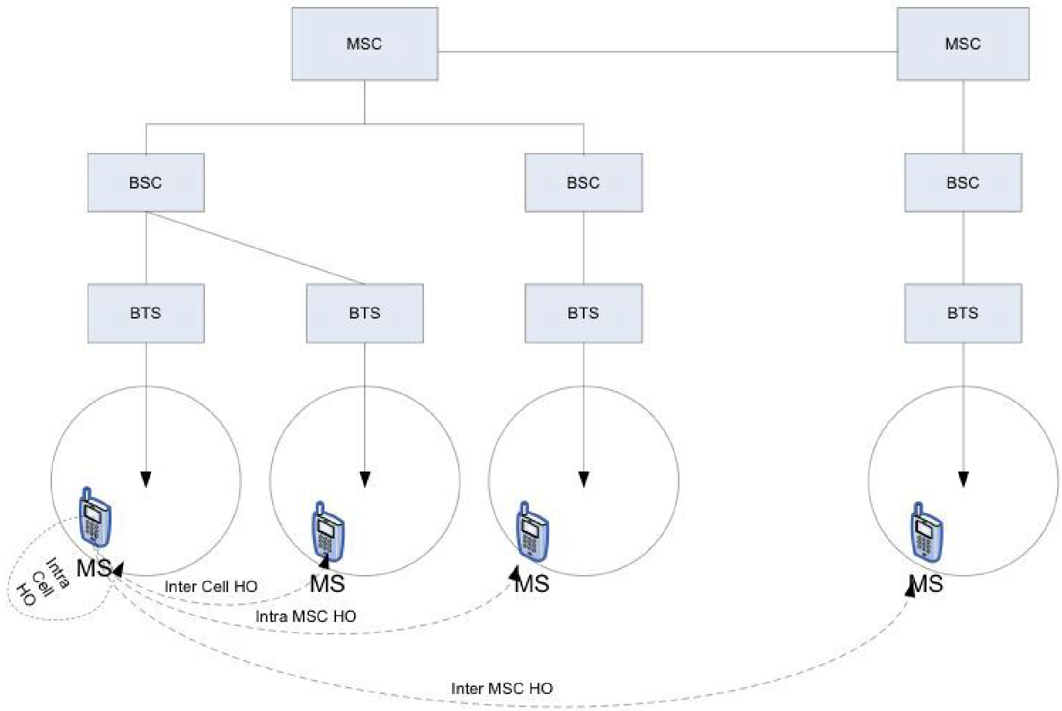


Fig. 5. Handoff types in GSM

- Inter-MSC handover: when the MS travels between two cells belonging to two different BSCs controlled by two different MSCs.

Another classification is based on whether the MS or the network initiates the handoff. They are i) mobile-initiated, and ii) network-initiated with mobile-assisted. Fig. 6 illustrates the information flow during the intra-MSC handoff process. First, the MS sends to BTS_{old} the measurement reports. BTS_{old} forwards this message to BSC_{old}. BTS_{old} will then decide whether to handoff or not. If a handoff is necessary, the BSC_{old} sends a message requiring a handoff to the MSC. The MSC finds BSC_{new} in the received message and sends a request to handoff to the BSC_{new}. Then BSC_{new} finds the available resource to allocate the physical channel in the BTS_{new} to handle the arriving MS. When the MSC receives the acknowledgement from the BSC_{new}, the command to handoff is sent to BSC_{old}, BTS_{old}, and the MS. Next the link between the MS and the new BTS is established, and the one with the old BTS is released. This completes the handoff process.

Due to the popularity of GSM, a lot of research has been done on GSM handoffs. In [35], [36] we find a performance analysis model of handoff algorithms. In [37] this analysis is improved by making it more accurate with a discrete-time approach. Besides the analysis of handoff algorithms, many handoff algorithms have been proposed in [36], [38]–[41] to improve QoS in GSM, e.g., mobility-management based handoff (including position and distance), fuzzy-logic based hand offs, and neural-network based handoffs. However, recommendations of cellular networks do not specify a handoff algorithm. This work is usually done by the vendor. Thus, network operators and manufacturers are able to define and use a handoff algorithm based on the various parameters such as signal strength, bit error ratio. GSM can support both NCHO and MAHO. In MAHO, the handoff time between handoff decision and execution is approximately 1 second.

F. Handoff in WLAN

WLAN techniques are based on the set of IEEE 802.11 standards which are developed by the IEEE LAN/MAN Standards Committee (IEEE 802) for the 2.4 GHz and 5 GHz spectral bands. The basic handoff in WLAN is described in the IEEE 802.11 specification [42], [43]. This process performed in Layer 2 includes three phases as illustrated in Fig. 7:

i) Discovery: The discovery process can either be active or passive. In passive scanning, the MS listens to the broadcast beacon signal periodically sent by Access Points (APs). In active scanning, the MS actively sends a Probe Request to an AP signal receiver. Each AP which receives the probe will respond to the probe.

ii) Re-authentication: In this phase, the MS authenticates with the best suitable AP found in the first phase.

iii) Association: Once the MS is authenticated with the new AP, it sends a Re-association Request to the new AP. In response, the new AP sends a Re-association Response which contains the information regarding the supported bit rate, station ID, etc. The old AP is not informed by the MS about the change of the location. Inter-Access Point Protocol (IAPP) [44] is used to complete the last step of the handoff procedure. The IAPP uses two protocol data units (PDUs) to indicate that a handoff has taken place. These PDUs are transferred through wired network from the new AP to the old AP using UDP/IP.

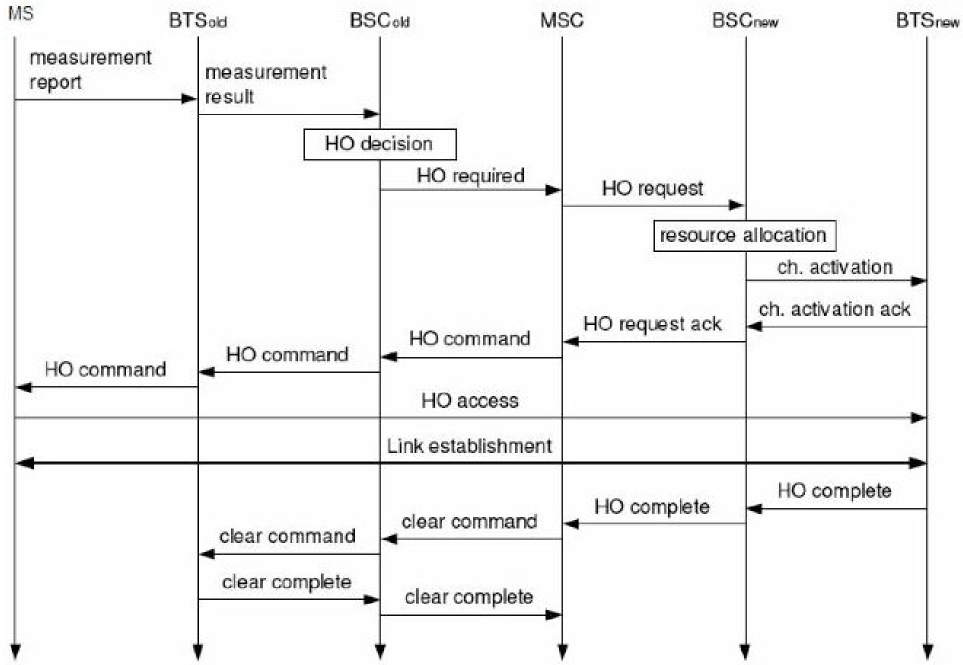


Fig. 6. Intra-MSC handoff in GSM

Handoff latency in 802.11 is much more than 50 ms [45], the interval is detectable with the human ear during a phone conversation, so the handoff latency is a challenge in handoff algorithms. Thus, fast handoff is essential for IEEE 802.11-based voice and video applications. From the point of view of the OSI model, the handoff algorithms work based on the measurement input from the Layer 3 (and above) or Layer 2 (and below) of the seven–layer OSI model. Common upper layer measurements are packet loss and roundtrip delay. Operating in Layer 2 - MAC, in [46]–[48] fuzzy logic and neural network based handoff algorithms are proposed to mitigate handoff latency in WLANs. In [48] the average signal strength and the variation in signal strength are used as inputs to the fuzzy logic algorithm. Approximately 70% improvement is achieved with handoff latency by the proposed handoff algorithm compared to conventional handoffs.

Link layer forwarding is the technique used in [49]. The proposed link-layer forwarding scheme includes two components: store/forwarding unit and the handoff detection, both implemented in the device drivers of the AP. In the first unit, the driver maintains a queue for each handoff, holding packets for forwarding. In the second unit, packets, which are not sent due to bad link quality, are forwarded to the new AP after handoff. The result is that the proposed scheme reduces packet loss during a handoff process in WLAN.

Another approach in Layer 2 is to use integrated SNR, load and association time (the period of time that an MS keeps communicating with an AP and without a handoff) as input to the handoff algorithms [50]. The numerical simulation results show that the proposed algorithm achieves a minimum number of handoffs by reducing unnecessary handoffs and balances the network load. But the proposed algorithm fails in reducing handoff latency because of the complexity of the algorithm.

In a combination of Layer 2 and Layer 3, we can find hierarchical handoff techniques proposed in [51]–[53]. In Layer 3, Mobile IP protocol provides an efficient, scalable mechanism for roaming within Internet. It allows mobile device users to move from one network to another while maintaining a permanent IP address. There are two versions supporting IPv4 [54] and IPv6 [55]. In [51] one-level and two-level hierarchical integrated 802.11-based WLAN/WAN for multimedia applications are introduced. IEEE 802.11 based APs are connected to a common Domain Access Point (DAP) in a hierarchical manner. In one-level architecture, DAP is connected to Internet through its corresponding Gateway Access Point (GAP). Two or more GAPs are connected to Inter-Domain backbone. In two-level architecture, Corresponding Access Point (CAP) is used to manage two or more DAPs. To access the Internet, CAP is then connected to GAP. Mobility of a MS within one DAP is considered as "local mobility" and mobility of a MS from one DAP to another DAP is considered as "global mobility". A hierarchical handoff scheme is proposed for these two scenarios. The proposed scheme is better than the standard MIP by about 20% to 25% with respect to the handoff latency. Hierarchical Mobile IPv6 works together with fast-handoff schemes to reduce the handoff latency to around 300 – 400 ms [53]. Seamless Mobile IP (S-MIP) in [52] builds on top of fast-handoff algorithm, hierarchical Mobile IPv6, and location tracking. S-MIP shows that it can provide the lossless handoff at the IP layer with minimal signaling overhead compared to hierarchical Mobile IPv6.

G. Handoff in UMTS

UMTS is known as the third generation mobile communication network led by 3GPP which is able to provide a range of

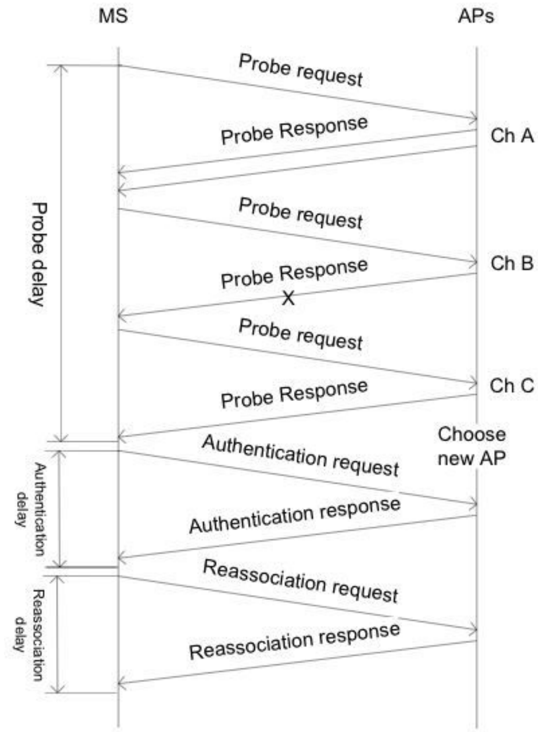


Fig. 7. IEEE 802.11 handoff process

TABLE II
A COMPARISON BETWEEN WLAN AND GSM/UMTS

Features \ Technology	GSM/UMTS	WLAN
Frequency	Licensed bands 900 MHz, 1800 MHz and 1900 MHz	Non-licensed band spectrum 2.4 GHz -5 GHz
Bandwidth	200 kHz/5 MHz	20 MHz
Cell Coverage	Large, 500 m up to 35 km	Small - up to 150 m (300 m in outdoor scenarios)
Multiple Access Scheme	FDMA,TDMA/CDMA	CSMA/CA
Switching	Circuit and packet-switching	Packet only
Network Architecture	BSS (BTS and BSC) NSS (MSC, SGSN, GGSN)	Access Point/Terminal
Data rate	9.6 kbps UMTS DL/UL:2 Mbps	Up to 54 Mbps
Services	Voice and data	Data communication oriented
Quality of Service	QoS mechanism allows real-time services	Best effort
Mobility	High, global (UMTS, UMTS-GSM)	Low (local)
Deployment cost	Expensive	Cheap
Applications	Fixed urban, Indoor, Pedestrian, Vehicular urban, Vehicular rural, High speed	Fixed urban, Indoor, Outdoor
Target market	Public	Home/Enterprise

3G services. A brief technical comparison of three networks, WLAN, GSM, and UMTS is illustrated in Table II. Due to the use of WCDMA in the physical layer, handoff in UMTS can be classified as [56]:

- Hard handoff: Hard handoffs are used for changing the radio frequency band of the connection between the User Equipment (UE) and the UMTS Terrestrial Radio Access Network (UTRAN) in UMTS, and changing the cell on the same frequency when there is no network support for macro diversity (where several antennas are used for transferring the same signal). These methods are selected when soft and softer handoffs are not possible.
- Soft handoff and softer handoff: are specialized handoffs used in CDMA implemented in UMTS. These methods are explained in detail in 3GPP specifications - TR 25.922 [57].

Because of the mobility of users and the range of 3G applications, it is important that the devices using UMTS should handoff to and from several other systems such as GSM, WLAN, and Bluetooth. Fig. 8 illustrates the handoff procedures from UMTS to GSM consisting of six steps [58]. A MS sends measurement reports to a UMTS node to answer the measurement request in Step 1. Candidate GSM cells are able to measure. Based on this measurement report from the MS, a Radio Network Controller (RNC) makes a handoff decision. The RNC sends a request to reserve resources to a MSC in Step 3. In Step 4, the MSC responds with an acknowledgement (ACK) combination with a handoff command to confirm. While receiving the ACK, the UMTS node sends to the MS the handoff command in Step 5. Finally, a handoff from UMTS to GSM is performed by sending a GSM Handover Access message to the BSC in Step 6.

Many handover management architectures for integrated WLAN/UMTS are proposed in [59]. They range from the solutions where the involved networks remain independent of each other with no joint resources to the solutions where one network is embedded in another and the control mechanisms and routing paths are shared. Most of them use Mobile IP to interconnect different technologies and support load balancing. The handover performance of these architectures is improved. But, there is the trade-off between the complexity of the implementation and the performance of the handover procedure. In [60], a framework for integrated broadband technologies (IEEE 802.11, IEEE 802.16e and Digital Video Broadcasting systems - DVB) and UMTS at radio access level have been proposed. The new version of UMTS has some changes mainly in UTRAN including modifications to MAC and Radio Resource Control (RRC) protocols. An inter-working unit (IWU) is also introduced between the WLAN and the RNC for integrating specific and radio-related issues. New types of handover between an AP and Node-B are specified as well as the APs themselves, which can be connected to the same or different IWUs: intra-IWU, inter-IWU, WLAN to UMTS, and UMTS to WLAN. Three proposed architectures are distinguished: the dependent architecture – data traffic is carried by the WLAN and the RRC signaling is confined to the WCDMA; the independent architecture – both bi-directional data traffic and the RRC signaling are provided within WLAN; the combined architecture that unifies the benefits of both architectures. Simulation results in [61] show that the dependent architectures and the combined architecture can achieve the best handoff performance while the independent architecture results in a bad performance although the

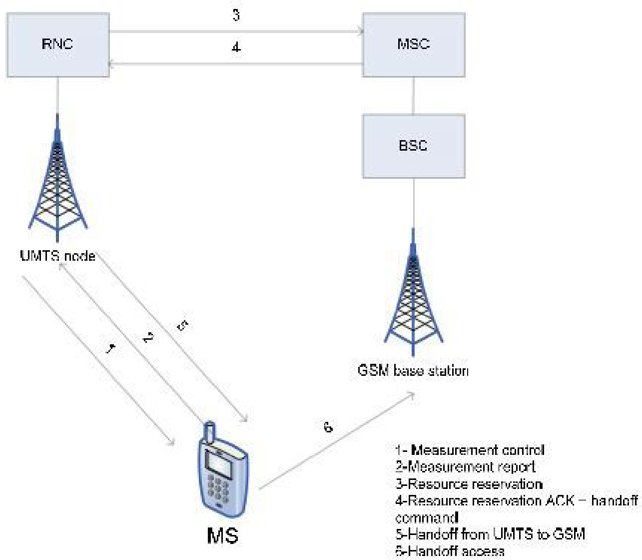


Fig. 8. Inter system handoff from UMTS to GSM

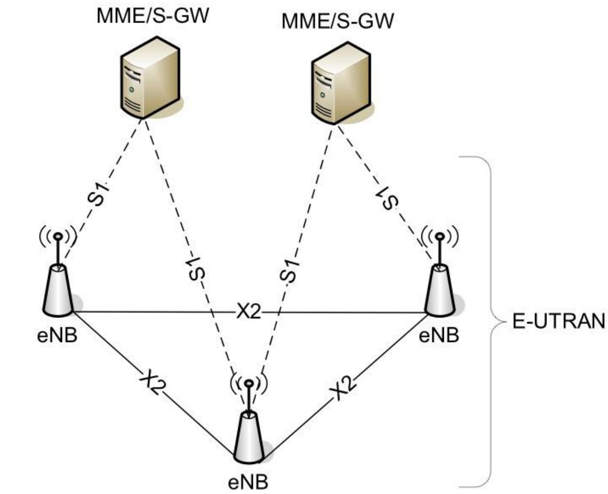


Fig. 9. E-UTRAN architecture

independent architecture specifies the least complex handover control and minimal power consumption.

H. Handoff in LTE

LTE, stands for Long-Term Evolution, is the latest standard of the 3rd Generation Partnership Project (3GPP), also known as Evolved UMTS Terrestrial Radio Access Network (E-UTRAN). This standard is an upgrading 3GPP UMTS to the 4G mobile communications technology. LTE is designed to meets the recent increase of mobile data usage and emergence of new applications such as Multimedia Online Gaming, mobile TV, Web 2.0. In order to achieve the performance requirements, LTE rely on physical layer technologies such as, OFDM and MIMO systems, Smart Antennas. It is hopefully to deploy the LTE products in real networks in 2011 by Verizon Wireless [62].

There are important changes also in Radio Access Network architecture, where the distribution of functions between the base station node, called eNodeB (eNB) and the central node, called the Gateway node are different compared to the functional distribution between NodeB and RNC in UMTS. The LTE architecture (Fig. 9) consists of eNBs, Mobility Management Entity (MME) and System Architecture Evolution (SAE) Gateway (S-GW) [63]. The eNBs connects to the MME/S-GW by the S1 interface and connects to each other through X2 interface. The main functions of the eNBs are: radio resource management and routing user plane data towards S-GW. This means that all radio control functions such as handoff control, admission control are terminated in eNB. The MME/S-GW performs the following functions: distribution of paging messages to eNBs; security control; encryption of user data streams; switching of U-plane to support of User UE mobility; idle mode mobility handling.

Unlike UMTS, there is no soft handoff support in LTE. In LTE, network controlled, UE assisted handoff is performed [63]. The eNBs makes the handoff decisions without involving the MME/S-GW. All necessary handoff information is exchanged between the eNBs via X2 interface. A handoff complete message is sent to the MME/S-GW once a new connection is established between UE and the target eNB. This feature can reduce the signaling load on the S1 interface. The main steps of the handoff procedure shown in Fig. 10 are: (1) When the UE needs a handoff, it sends a Measurement Report to the source eNB. The source eNB makes a handoff decision based on the Measurement Report and Radio Resource Management information. (2) The source eNB sends a HO Request to the target eNB. (3) The target eNB stores the context and the new Cell Radio Network Temporary Identify (C-RNTI) and responds to the source eNB with a response message: HO Request ACK. (4) once the source receives the HO Request ACK, it transfers all information to the UE in the HO Command message. (5) The UE sends a HO Confirm to the target eNB when it makes a successful radio handoff. At this time, the target eNB starts transmitting data buffered from the source eNB to the UE. After that the target eNB sends the path switch command to MME/S-GW and finally, it triggers the release of resources from the source eNB in steps (6), (7) and (8). During Detach Time the UE is disconnected from the source eNB and not connected to the target eNB. The handoff in LTE has minimum interruption time, less than that of circuit-switched handovers in 2G networks such as GSM. Investigations in [64], [65] show that the LTE can achieve a good handoff performance in terms of user throughput, handoff delay and handoff failure rate.

Handover from LTE to 2G/3G systems are designed to be seamless. Handoff between LTE and WLAN has been standardized in [66]. A seamless handoff scheme for interworking between LTE and 3G Circuit-Switching systems is proposed in [67] to reduce the service interruption time which is required less than 300 ms by 3GPP in [68].

I. Handoff in Mobile WiMAX

Wireless Interoperability for Microwave Access (WiMAX) as the broadband wireless access technology is built on the robust OFDM/OFDMA physical layer which can work with large delay in NLOS environment. There are two flavors of WiMAX: fixed WiMAX and mobile WiMAX. Fixed WiMAX

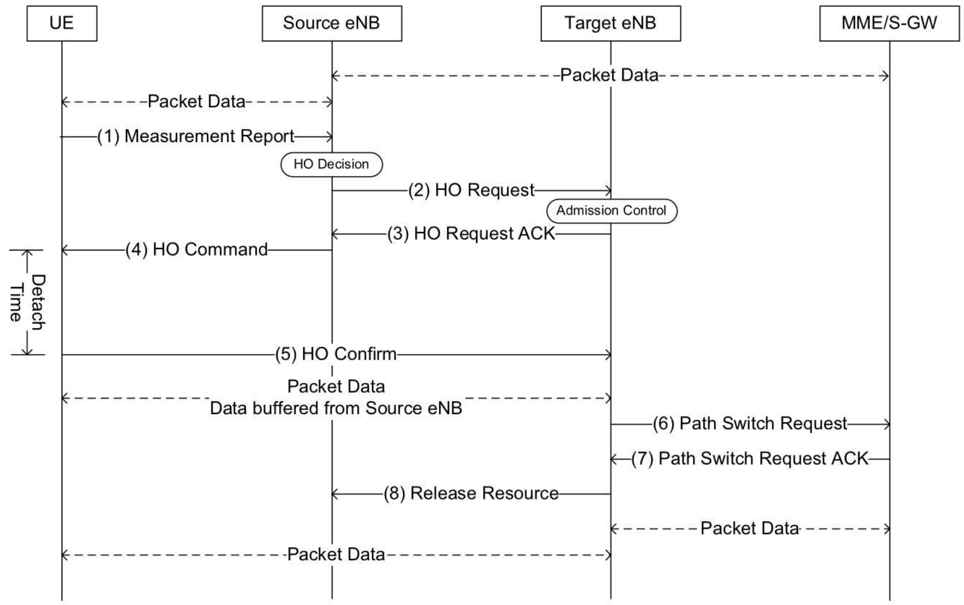


Fig. 10. Message chart of the LTE handover procedure [63]

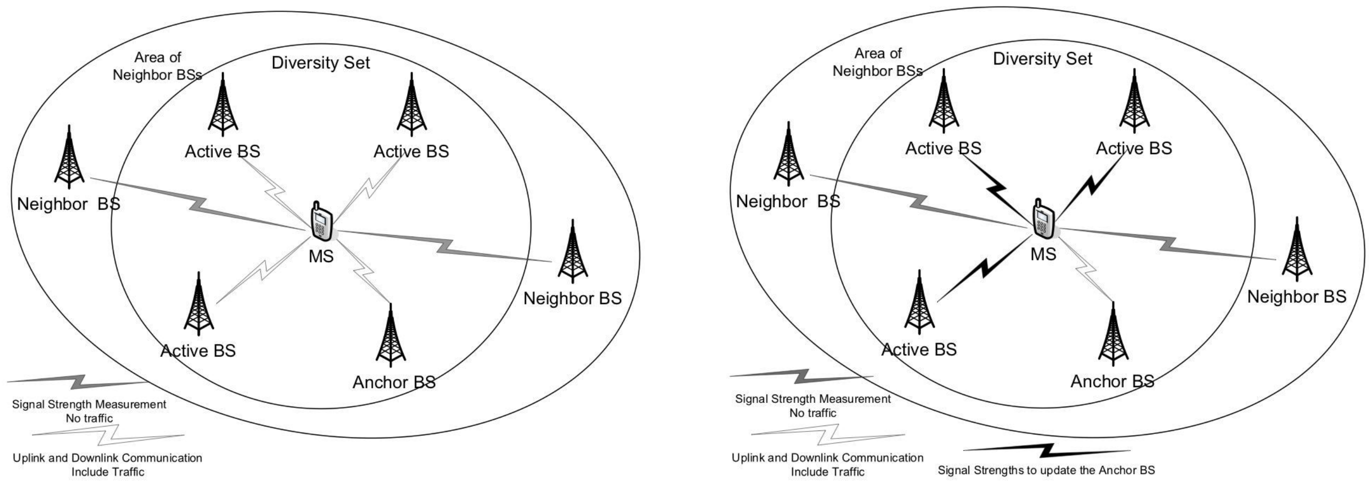
is based on IEEE 802.16–2004 standard [69] and is optimized for fixed and nomadic applications in LOS and NLOS environment. Fixed access allows no movement. Nomadic access provides movement among cells but there is no handoff support. Mobile WiMAX is based on IEEE 802.16e standard [70] and targeted for portable and mobile application in NLOS environment. However, Mobile WiMAX systems can also provide fixed and nomadic access. Mobile WiMAX incorporates more additional features such as: handoff, flexible power management (sleep and idle mode), channel bandwidth scalability (SOFDMA), fractional frequency reuse, and better NLOS performance and indoor penetration. Mobile WiMAX can provide broadband access to stationary as well as mobile users at the speed up to about 120 km/h. These applications can be provided by Mobile WiMAX: music/video streaming, live TV broadcast, voice/video chatting, Internet multiplayer game, large file download/upload from/to Internet, remote access to office LAN via VPN. Mobile WiMAX can make broadband available everywhere (i.e. at home, in the office, on the street, on train). A brief comparison between Mobile WiMAX and LTE is given in Table III. LTE is better suited for global adoption than WiMAX. LTE also offers MSs better coverage as they travel by providing seamless handoff and roaming for true mobility. However, LTE commercial products will be delayed until 2011, meanwhile WiMAX is being deployed widely since 2009 [73].

Three types of handoffs are defined in Mobile WiMAX: i) hard handoff, ii) Macro Diversity handoff (MDHO), and iii) Fast Base Station Switching (FBSS). Hard handoff in WiMAX is the default handoff mechanism while the last two types are optional and soft handoffs. The WiMAX Forum has developed several techniques to optimize hard handoff within the framework of the 802.16e standard. In both FBSS and MDHO, the MS and BS maintain a list of BSs involved with the MS's handoff, so-called "diversity set". A diversity set is defined for each MS in network. Among the BSs in the diversity set, an Anchor BS is defined. This is the BS where the MS is registered, synchronized. In MDHO, the MS communicates with all BSs in its diversity set. An MDHO begins with a decision for an MS to transmit to and receive from multiple BSs at the same time. For a downlink, all BSs in the diversity set transmit data to the MS such that the MS performs the diversity combining. For an uplink, the transmission of the MS is received by multiple BSs where selection diversity of received information is performed. In FBSS method, the MS only communicates with the Anchor BS for all uplink and downlink traffic including the management of messages. This is also the main difference between MDHO and FBSS. An FBSS handover is a decision by an MS to receive or transmit data from a new anchor BS within the diversity set. Switching from one Anchor BS to another is done without proceeding HO signaling message.

The standard specifies a highly flexible and scalable Layer 2 (MAC layer) handoff policy, allowing the MS, the BS and the network to initiate and optimize handoffs. The comparison of WiMAX handoff procedures presented in [71] has shown that both soft handoff methods achieve better performance in comparison to hard handoff method. With soft handoff methods the best service disruption time is less than 50 ms with very low packet loss (less than 1%) [70]. Meanwhile, the minimum handoff time of three levels of hard handoff are evaluated in [72]: 280 ms, 230 ms and 60 ms. Hard handoff method can be a choice to deploy due to low cost and low complexity. However, the existing handoff mechanisms in WiMAX is challenged with latency, packet loss and optimization of channel resources [71].

J. Comparison of handoff in WLAN, GSM/UMTS, LTE and WiMAX

Table IV shows a brief comparison of handoff in WLAN, GSM, UMTS, LTE, and WiMAX. In general, handoff in these wireless technologies has similar processes within the three



(a) MDHO (b) FBSS

Fig. 11. Mobile WiMAX soft handoffs: (a) MDHO and (b) FBSS.

TABLE III
A COMPARISON BETWEEN WIMAX AND LTE

Features	LTE	WiMAX
Legacy	GSM/GPRS/EGPRS/ UMTS/HSPA	IEEE 802.16 a through 16d
Core network	U-TRAN moving towards All-IP Evolved UTRA CN with IMS	WiMAX Forum All-IP network
Frequency band	2 GHz	2.3 GHz; 2.5 GHz; 3,5 GHz; 5.8 GHz (unlicensed)
Channel bandwidth	Up to 20 MHz	Up to 20 MHz
Downlink Uplink	OFDMA SC-FDMA	OFDMA OFDMA
Peak data rate	DL: 100 Mbps, UL: 50 Mbps	DL: 75 Mbps, UL: 25 Mbps
Cell radius	5 km	2–7 km
Cell capacity	>200 users at 5 MHz; >400 users with larger BW	100–200 users
Mobility support	Up to 350 km/h	Up to 120 km/h
Mass market	2011	2009

phases: measurement, decision and execution. We summarize their characteristics here:

- Handoff in such networks is usually based on the channel measurements which consist of Relative Signal Strength (RSS) and/or CIR. Other measurements such as mobility, traffic, QoS, and cost (for vertical handoff) can also be good input for making a handoff decision.
- UMTS prefers soft handoffs since it uses WCDMA at the physical layer and it uses hard handoff as an alternative, while WLAN and GSM use hard handoff. In WiMAX, hard handoff is mandatory, soft handoffs are optional. Unlike UMTS and WiMAX, LTE do not support soft handoff.
- GSM, UMTS, and WiMAX can support both NCHO and MAHO because of their centralized approach. WLAN prefers MCHO due to this; it reduces the overall complexity in the network, the signaling overhead, and the handoff latency more than a mobile-assisted handover (MAHO). But in both cases, the channel monitoring is performed at the terminals.
- These networks can use all types of algorithms, based on the measurements from any layer (normally from Layer 1 to Layer 3). They also use intelligent technologies such as fuzzy logic, and pattern recognition to improve the performance of handoff algorithms.
- Both LTE and WiMAX require reducing handoff latency less than 50 ms. LTE is better than the existing versions of WiMAX. IEEE 802.16m could be a competitor of LTE.

K. Handoff Issues in 60 GHz-based Wireless Systems

When compared to the cell size of GSM, UMTS or 802.11 WLAN, the cell size of 60 GHz network is small, i.e., in the order of 10 m. Fig. 1 shows the difference in coverage between a 2.4 GHz network and a 60 GHz network; there are only three base stations to cover the whole area for 2.4 GHz radio, but at 60 GHz it is necessary to install at least one antenna per room. Due to small cell size, even a small movement of the MS may trigger a handoff [11] and this may lead to a large number of handoffs during a call [13], [83]. The second issue is the smaller overlapping area between the cells. With GSM, UMTS, 802.11 WLAN, the larger overlapping area between cells allows the network elements enough time to initiate and complete a handoff successfully. In 60 GHz networks, the overlapping area is much smaller. Especially in indoor environment, the overlapping area usually exists in and around open areas like windows, and doors (Fig. 1). When a MS exits a room through a door, the MS can make a sharp turn (for example: turn left or turn right). In this case, the overlapping area might be too small to give the MS sufficient time to complete a handoff if not identified early enough. This phenomenon is termed as the corner effect.

Let us get an impression of the time taken for handoff in 60 GHz systems in the indoor environment. We assume that the speed of movement of a person is 2 m/s and it takes 5 s to pass through a cell (room size being 10 m×10 m). This means that for every 5 s a handoff will be performed. The

TABLE IV
A COMPARISON HANDOFF IN WLAN, GSM/UMTS, LTE AND WIMAX

Features \ Technology	GSM/UMTS	WLAN	LTE	WiMAX
Handoff process	Measurement, Handoff decision, Execution	Discovery, Reauthentication, Reassociation	Preparation (measurements and decision), Execution, Completion (HO notify)	Cell reselection, HO decision and initiation, synchronization and ranging
Handoff type	Hard handoff; UMTS: soft handoff	Hard handoff	Hard handoff	Hard handoff (mandatory), soft handoffs (optional)
Handoff controlled	Network (rarely at MS)	MS	eNB	MS and Serving BS
Handoff latency	–	–	<50 ms	802.16e: 35–50 ms; 802.16m: <30 ms

time allowed for completing a handoff with a 1 m overlapping area at an open door is $t_{handoff}$ = 0.5 s.

Another issue is the propagation attenuation of the 60 GHz channel by the surrounding obstacles. Objects such as furniture can cause shadowing, and also humans can block signal, with attenuation of signals by 20 dB from the link budget if the LOS path is blocked. Thus handoff is rather challenging in a crowded room. As mentioned above, SIR can drop from 20 dB to 0 dB and rise up to 15 dB again in a few centimeters. If a handoff is triggered due to that reason, it is an unnecessary handoff. Handoff algorithm should consider this situation.

Lastly, 60 GHz band is applied in Radio over Fiber networks in many instigations [2], [6], [11], [13], [74]–[77]. In such network, signaling during a handoff process could be affected by the additional propagation delay for transmitting signal in the optical network in RoF network. In [79], radio over fiber system can achieve a good performance in both downlink and uplink signal in case the optical length is over 25 km. This could also contribute to a significant propagation delay which is much more than the propagation delay for transmitting signal over air.

In recent years, several investigations on the 60 GHz band and its handoff have been proposed [2], [6], [11], [13], [74]–[77]. Most investigations have introduced the new appropriate network architecture to solve handoff issues at 60 GHz radio. In [6], the authors extended the concept of Virtual Cellular Network (VCN) in [75] for 60 GHz communication with multiple receiving antennas to form a MIMO system. The VCN architecture utilizes the idea of Single Frequency Networks and distributed Access Points (AP) to form an adaptive wireless infrastructure. In a VCN, there is no conventional Base Station (BS) that manages the channel and handovers. Instead, the notion of "ports" - essentially simple antennas - has been introduced. In a network area, all the ports are connected to and controlled by a Port Server (PS). In this system, a Virtual Cell (VC) is dynamically formed for each and every MS. It is defined as the area in which the signals sent from the MS are strong enough to capture a port. Packets destined to an MS are dynamically routed by the PS to all the ports inside the VC. Since the network operates at a single frequency channel and a VC is always created to follow an MS, there will be no conventional handover. Each time the MS moves to a new position, a new VC is created and the routing table must be updated in the PS. The drawbacks are twofold, first the whole spectrum is shared by a large number of users; second, higher traffic overhead to handle the ports dynamically.

The authors in [11] have proposed the Radio over Fiber (RoF) indoor network employing the novel concept of Extended Cell (EC). ECs are dynamically created by grouping several adjacent radio cells. This means adjacent antennas (referred as radio cells) are allowed to transmit the same content over the same frequency channel. Multipath and shadowing effects in such networks are solved by employing Orthogonal Frequency Division Multiplexing (OFDM) technology. Now the overlapping area is the overlap area between two adjacent ECs in RoF indoor networks. So the handoff performance is improved. The simulation results show the number of handoffs is reduced significantly and the probability of a handoff drop for the case using EC to be less than that in the case where EC is not used is up to 70%. Two architecture for future home networks using 60 GHz have proposed in [2]: cell-based communication infrastructure using the EC concept and Ad hoc based home network communication infrastructure. The challenges and research issues in proposed architectures include connectivity, mobility, self-configuration, cognitive networking.

Handoff issues in railway communication have been presented in [13]. The authors state that if a 100 m train moves with a speed of 100 km/h, handoff is carried out frequently with a period of 1 s. The Moving Cell (MC) concept is applied to solve those problems. The MC is based on the previous physical moving cell concept proposed in [82]. MC is a group of adjacent radio cells that moves together with the train. It can communicate on the same frequency during the connection. This avoids most handoffs when the train moves. The advantage of Radio over Fiber techniques and the characteristic of train network (directional network), the proposed architecture could be the promise solution to provide passengers in the train with the broadband Internet. Unfortunately, this concept might not be applicable for indoor environments where a large number of users move differently. The concept Moving Extended Cell (MEC) proposed in [76] for Radio over Fiber networks may gain benefits of two above concepts: EC and MC and Virtual Cell Zone [80]. An EC is formed by 7 adjacent cells and the data emission frequency is the same in every single cell. Each user has been covered by the 7-cell EC which moves together with the user. The simulation results show the proposed architecture can achieve zero CDP and packet losses for mobile speed up to 40 m/s and mitigate the corner effect phenomena. The authors suggest that Radio over Fiber network at 60 GHz can apply for both indoor pedestrian and vehicular communications.

In [74], a new MAC scheme, Chess Board Protocol, has been presented to Radio over Fiber networks at 60 GHz. This protocol bases on frequency switching codes. The bandwidth is divided into 2M channels where M channels are used for uplink transmission and the other M channels are used for downlink transmission. Every BS supports all channels. To request permission for uplink transmission on a channel, the MH sends a request to the control station using the reservation field in any slot in this channel. The analysis in [74] show the proposed MAC scheme can support QoS requirements and make a fast and easy handoff. The proposed MAC scheme can also be used for indoor and outdoor communication at 60 GHz.

In [78], [81] directional antennas for 60 GHz systems has been present. In this paper, MAC and routing protocol are also described. The enhanced MAC reduces the problem of hidden node due to directional antennas. Handoff can take into account the usage of directional antennas. The signal strength of the beacons sent out omni-directionally by APs is smaller than that of packets sent out directionally with the same transmitted power. Normally, handoff is triggered when the RSS of the associated AP is below a fixed threshold. In a fast handoff approach, handoff is performed when the RSS of a new AP is greater than that of the current AP plus with a reasonable hysteresis.

Due to the vulnerable nature of 60 GHz LOS links, vertical handoff from 60 GHz radio to WLAN is the proposed solution to overcome that feature [77]. The handoff decision algorithm is designed as cognitive approach and based on decision theory with multiple factors such as: user preference, network condition, the capacity of the terminal. The proposed decision theory based decision algorithm is compared to three naive algorithms: i) algorithm "r" that chooses randomly networks, ii) algorithm "s" that always switches to WLAN when LOS is blocked, and iii) algorithm "w" that always waits for 60 GHz recovery. The simulation results show the proposed algorithm is able to make a handoff in uncertain situations.

IV. Handoff Algorithms

Based on the handoff criteria, handoff algorithms can be classified into two classes [84] [85]:

i) Conventional handoff algorithms – these algorithms are based on the signal strength, distance, velocity, power budget, and SIR.

ii) Intelligent handoff algorithms – these are based on AI technologies such as fuzzy logic, prediction, pattern cognition, and neural networks.

A. Conventional Handoff Algorithms

Relative Signal Strength (RSS). In this method, the RSSs of BSs are measured over time and the BS with the strongest signal strength is selected to carry out a handoff. For example, when a MS moves to the point A (Fig. 12), the RSS of BS_2 exceeds the RSS of BS_1 and the MS will be handed over to BS_2. If the RSS of BS_2 falls below that of BS_1, the MS is handled back to BS_1. Due to multipath fading the signal may fluctuate, several handoffs may be requested while BS_1's RSS is strong enough to communicate with the MS. This results in the undesirable so-called ping-pong effect. Handoff in this case is unnecessary. These unnecessary handoffs will increase the probability of a call failing during a handoff and the network load. The handoff techniques to overcome this problem have been introduced in [3] and they are: Relative Signal Strength with Threshold, Relative Signal Strength with Hysteresis, Relative Signal Strength with Hysteresis and Threshold. Let us explain these techniques:

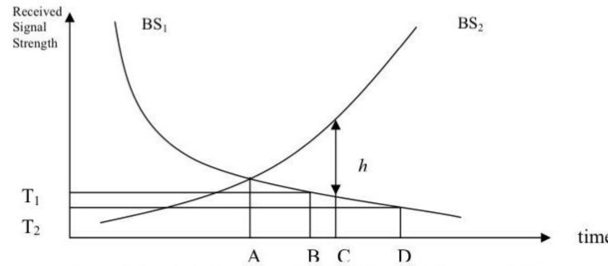


Figure 8. Received signal strength when MS travels in the handoff area

Fig. 12. Received signal strength when MS travels in the handoff area

i) Relative Signal Strength plus Threshold: The handoff is requested if and only if the RSS of BS_1 is lower than the threshold value and the RSS of BS_2 is stronger than that of BS_1. In Fig. 12, T_1 is set as the threshold value and handoff is carried out at the point B. This technique helps the network limit handoffs when the signal from the current BS (BS_1) is strong enough. But the problem is to find the appropriate threshold value. If the threshold is too low, the call may drop. If it closes to the point A, the ping-pong effect can still persist.

ii) Relative Signal Strength with Hysteresis: This technique allows handoff if BS_2's RSS is stronger than that of BS_1 with a hysteresis value h. Fig. 12 illustrates this technique with the hysteresis value h and the handoff is at C. This technique can avoid effectively the ping-pong effect, but the problem is the same as that of the above technique i.e., to find the appropriate hysteresis value. If h is too high, the current signal (from BS_1) may fall to a very low value and the call may be dropped. If h is too low, handoff may happen unnecessarily, while the signal strength is enough to maintain the ongoing call.

iii) Relative Signal Strength with Hysteresis and Threshold: This technique combines both the threshold value and the hysteresis value to minimize the number of handoffs. The rule is, handoff takes place if BS_1's RSS is lower than the threshold value and BS_2's RSS is stronger than BS_1's RSS by the hysteresis value. For example, the handoff point will be around the Point C in Fig. 12. This method is used in the GSM standard.

Fig. 12 also shows value T_2 which is known as the receiver threshold. It is the minimum value of received signal strength that makes sure that the call continues. If the received signal strength is less than T_2, the ongoing call will be dropped. The time interval from the point A to the point D enables the network to delay the handoff request until the receiver threshold is reached. During this time the network can allocate resources for the MS in the target cell.

The performance of handoff algorithms using both absolute signal strength and relative signal strength measurements are explained in [86]. The authors use Expected Average Signal Strength of a base station for handoff decisions. This scheme helps in avoiding the unnecessary handoffs. In [37] a model is proposed to analyze the handoff algorithms using both absolute and relative signal strength measurements. The benefit of these techniques is, it is simple to implement, thus making them popular in the cellular systems such as: GSM, UTMS and WLAN.

SIR Based Algorithms. Signal to Interference Ratio (SIR) is a measure of the communication quality. This method allows handoff if the SIR of the current BS is lower than the threshold and the SIR of the target BS is better. In [17] an SIR based handoff algorithm is proposed, where each user aims for a target SIR γ_t and handoffs are allowed when the absolute SIR drops below a threshold, γ_{ho} (normally less than γ_t). But this algorithm causes cell-dragging that happens when a MS is moving slowly away from a cell and the BS do not recognize it due to strong average signal. This algorithm also inhibits handoffs near the geographical cell boundaries.

Velocity Based Algorithms. If the user moves fast, the probability of call drop may be high due to excessive delay during handoff. In [38] a fast handoff algorithm with velocity adaptation is proposed for urban communication. Velocity estimators using LCR, ZCR and Covariance methods are used. Corner detection algorithm is also incorporated into the handoff algorithm to speed up handoffs in NLOS scenario. The paper shows that velocity adaptive handoff algorithm performs well in a typical NLOS scenario of urban cellular network by reducing handoff delay.

The velocity adaptive handoff algorithm using multi-level threshold is presented in [87]. The handoff threshold values are assigned according to the velocity of the users. Since low speed users spend more time in the handoff area, they are assigned higher thresholds. High speed users are assigned lower thresholds. The simulation result in [87] shows that when the number of levels for threshold is increased from one level to 8 levels, the blocking probability and handoff failure probability is significantly reduced.

Direction Biased Algorithms. Direction biased algorithms are important for high mobility users especially in NLOS handoff (for example NLOS handoff) [88]. In this algorithm, base stations are divided into two groups. Group-1 has the base stations that a MS approaches and Group-2 has the base stations from which the MS moves away. Two hysteresis values are used for handoff initiation: h_e for Group-1 and h_d for Group-2 where $h_e < h < h_d$. The direction biased algorithm improves handoff performance by lowering the mean number of handoffs while reducing the handoff delay. In [89], the author uses the same mechanism for handoff in Distributed Wireless Communication System (DWCS).

Minimum Power Algorithms. In [18] the authors proposed Minimum Power Handoff (MPH), which uses transmission power as a handoff criterion. MPH looks for a pair of BS and a channel that has a target SIR with minimum transmitted power. The simulation results show that this algorithm reduces call dropping but causes a high number of unnecessary handoffs. In order to reduce the number of handoffs, handoff requests are delayed by using a handoff timer in MPH (MPHT). If MPHT finds the best BS that differs from the currently serving BS, the maximum SIR at the current BS is calculated. If it is less than the minimum required SIR, handoff is carried out immediately; otherwise the timer is activated. Handoffs are delayed until the timer reaches a given value. When the handoff is executed, the algorithm turns off the timer.

Conventional handoff algorithms can use the signal strength, SIR, power as its inputs. These algorithms are simple and easy to implement but their poor performance can make them difficult to use in 60 GHz systems. In order to apply in 60 GHz systems, these algorithms should reduce the number of handoffs while reducing the handoff delay. This is really a challenge to conventional handoff algorithms. To reduce both the number of handoffs and the handoff delay, an adaptive hysteresis mechanism is required. In addition, the algorithms utilize the velocity and direction information of a MS to bring in the improvement.

B. Intelligent Handoff Algorithms

Fuzzy logic based handoff algorithms. In [90], a fuzzy logic handoff algorithm is presented. Heavy fading makes the area unstable in which hysteresis used in conventional handoffs may not be sufficient. The signal intensity of the adjacent base station is used for fuzzy system. The analysis results in [90] show a low frequency of handoff and thus handoff stability is enhanced. In [91] the proposed handoff algorithm based on multiple criteria cell membership is proposed, which include relative signal strength, traffic level, location of a MS and the time of the last handoff. The number of handoffs is reduced without excessive cell overlapping.

Fuzzy logic used in [92] finds out the appropriate RSS threshold and the RSS hysteresis for conventional handoff algorithms. Based on pre-selection algorithm in [88], an adaptive direction biased fuzzy handoff algorithm is proposed. The input of the fuzzy system includes RSS, SIR, velocity of a MS, and traffic. The simulation results show that this algorithm helps in reducing both the number of handoffs and the handoff delay.

In [93] fuzzy logic is used to find the handoff factor for each BS using the set of input – RSSI, link quality, and distance between MS and BS. If the handoff factor of the current BS is larger than that of the target BS, a handoff is requested. [93] shows that the handoff factor can help to resolve the corner effect problem. The handoff factor is also used in a fuzzy logic vertical handoff in [94].

Neutral based handoff algorithms. Neural network based handoff algorithms are presented in [95]–[97]. In [95] a handoff algorithm based on hypothesis testing and implemented by neural network is proposed. The input of neural network is only the signal strength received by a MS. The proposed algorithm can avoid excessive delay and exploit traffic measurements. However, no simulation result is presented. Simulation results in [96] show that the artificial neural network is suitable for multi-criteria handoff algorithms. A neural network using radial-basis functions is used for handoff algorithm [97]. The simulation results show that this algorithm reduces unnecessary handoffs as well as blocking rate.

Pattern recognition based handoff algorithms. In [98] the author uses pattern recognition technique (PR) to solve handoff problem. PR identifies meaningful regularities in noisy or complex environments. These techniques are based on the concept that, points in a feature space are mathematically defined and are close enough to represent same kind of objects. Algorithms include: (1) Explicit methods in which the samples are classified depending on the side of a set of hyper-surfaces they belong to; (2) Implicit methods based on the distances to a certain predefined representative vector in each group with fuzzy classifier algorithms (recognition by weighted distance and similarity vector) and clustering algorithms. The simulation result shows that the number of handoffs reduces significantly.

In [99], a pattern recognition handoff algorithm (PRHO) is introduced. This algorithm trains on the signal strength measurements at the location in which handoffs may be desired. Patterns are collections of signal strength measurements from BSs. When signal strength measurements match these patterns, a handoff can be carried out without much delay. This algorithm performs better than the traditional handoffs at the same threshold and hysteresis while reducing both the number of unnecessary handoffs and the handoff decision delay. However, setting the threshold and the hysteresis is still a problem of PRHO. To reduce corner effect, PRHO is extended by using a two-stage decision machine – regular and alert [100]. In the alert stage, three short patterns are defined by the users' direction. Matching the pattern located before the corner, the algorithm does not perform a handoff, but goes to the alert stage. In alert stage, each short pattern is compared with the signal strengths. Each short pattern has the appropriate handoff. This extended algorithm also gets better performance than the traditional handoffs.

Prediction based algorithms. Handoff algorithms can use the predicted value of handoff criteria such as RSS to make handoff decisions [101]–[103]. In [102], an adaptive prediction-based handoff algorithm is proposed to reduce the number of handoffs. There are different handoff priorities in this algorithm according to the predicted signal strength. A handoff is initiated following these priorities. The effect of the proposed algorithm on the handoff delay is not studied. In [101], a handoff algorithm using Grey prediction is introduced. Grey prediction uses the signal strength averaging function in traditional handoff algorithms. The simulation shows that the proposed algorithm minimizes both handoff delay and the number of handoffs. The algorithms presented in [103] use Grey prediction to predict signal strength for the input of fuzzy decision system. These algorithms result in good performance and even reduce the corner effect.

Clearly, intelligent handoff algorithms are much more complicated than conventional handoff algorithms. However, these algorithms can meet the requirements of 60 GHz systems. All mentioned intelligent algorithms can keep both the number of handoffs and the handoff delay low. Some of them are shown to improve the new call blocking probability and the handoff blocking probability. About their inputs, beside normal inputs such as: the signal strength, and SIR, intelligent algorithms use additional information of the MS such as: speed, direction, location and information of network such as: traffic. Thus, 60 GHz systems should deploy more functional systems to provide intelligent algorithm with that information.

C. The Comparison of Handoff Algorithms

The common performance metrics used to evaluate handoff algorithms in [35] are listed below and compared in Table 4:

1) Input parameters in handoffs are usually signal strength, SIR, BER, velocity, and direction. Conventional handoff algorithms use one or two of them as input. With intelligent handoff algorithms the input parameters are more.
2) The number of handoffs can be used for calculating handoff rate (number of handoffs per unit of time) and the number of handoffs per call. Conventional handoff algorithms can reduce the number of handoffs by using the hysteresis. The algorithms with velocity input and direction based support reduce the handoff delay while decreasing the number of handoffs. The results in [101], [103]–[105] show that the number of handoffs is reduced by intelligent handoff algorithms.
3) Ping-pong effect can be avoided in both conventional handoff algorithms and intelligent handoff algorithms by using the threshold value and the hysteresis value. Ping-pong effect still exists if the hysteresis value is small. However, the high hysteresis causes more handoff delay.
4) Handoff latency is an important parameter to analyze the handoff algorithms. This is high if conventional handoff algorithms assign the high value to the hysteresis for avoiding ping-pong effect. Intelligent handoff algorithms have a mechanism to reduce the handoff delay and the number of unnecessary handoffs so the latency is low.
5) Unnecessary handoff is caused by ping-pong effect. The number of unnecessary handoffs can be limited by using the hysteresis. Conventional handoff algorithms make a tradeoff between the number of handoffs and the handoff delay. As mentioned above, intelligent handoff algorithms can keep this parameter low. Integrated resource management handoff algorithms, SIRBH and MPH make a lot of unnecessary handoffs. MPH algorithm makes 4-10 handoffs per call compared to 1.5-2.5 handoffs per call of SIR-based handoff algorithm.
6) Corner effect is a serious problem in wireless communication. Velocity adaptive handoff algorithm and direction-biased handoff algorithm show good results while dealing with this problem. Using combination of velocity, direction information and AI techniques, the intelligent handoff algorithms can reduce its effect well.

In addition, the handoff blocking probability and new call blocking probability of the conventional handoff algorithms are higher than that of fuzzy handoff algorithms, 0.15 and 0.24 compared to 0.05 and 0.13, respectively [84]. There are many parameters mentioned while analyzing models [35] which we do not discuss here in this paper. Some of them are call dropping probability, the duration of interruption, and additional network traffic caused by the handoff.

TABLE V
THE COMPARISON OF HANDOFF ALGORITHMS

Features \ Handoff Algorithms	Conventional Handoffs						Intelligent Handoffs			
	RSS based	RSS plus with the threshold and/or the hysteresis	SIR based-SIRBH [17]	Minimum power - MBH [18]	Velocity Adaptive [38], [87]	Direction Biased [88]	Fuzzy logic based [91], [92]	Neural network based [97]	Prediction based [101]–[103]	Pattern Recognition based [98], [99]
Resource Measurements	Signal Strength	Signal Strength	Integrated resource management, SIR	Integrated resource management, Power, SIR	Velocity, Signal Strength	Direction, Signal Strength	Multiple inputs (RSSI, SIR, velocity, direction, traffic, etc)			
Ping-pong effect	Yes	Avoided	Avoided (by using the hysteresis)	–	Avoided	Avoided	Avoided	Avoided	Avoided	Avoided
The handoff latency	–	Increased	–	–	Reduced (2 m when using corner detecting)	Reduced	3 s-6 s (based on velocity adaption)	-	Reduced	Reduced
The number of Handoffs	–	Reduced	–	–	–	Low	Reduced (37% for LOS and 31% for NLOS)	Reduced	Reduced	Reduced
The number of unnecessary handoffs	–	Reduced	Lower than MPH (1.5-2.5 handoffs/call)	Greater than SIRBH (4-10 handoffs per call)	–	–	Low	Low	–	Low
Corner effect (NLOS)	–	–	–	–	Yes	Yes	Yes	–	Yes	Yes

V. VERTICAL HANDOFF

Hybrid mobile network (inter-system) is a trend in modern telecommunication systems to adapt to the high and mixed demand of users who want to use several services simultaneously. Two or more different communication systems are interconnected to sustain a seamless connection when a MS moves from one network to another and achieve the goals of mobility, power consumption, coverage, and low cost, etc. The technical communication systems range from wire-line LAN, WLAN, GSM, GPRS, Bluetooth, WiMAX, UMTS and LTE. There are two main scenarios in vertical handoffs: moving into the preferred network and moving out of the preferred network, which are known as moving-in and moving-out vertical handoffs. In [108] the authors state vertical handoff as two-fold, handoff from the underlay network to overlay network, and handoff back from overlay network to underlay network. The handoff between WLAN (underlay network) and GPRS (overlay network) is an example of vertical handoff (Fig. 13). Some investigations of vertical handoff are also discussed in the previous sections. The primary challenges in the design of the vertical handoffs are [107]:

- Low latency handoff – to switch between networks as seamless as possible with as little data loss as possible.
- Power savings – minimizing power drain due to simultaneously active multiple network interfaces.
- Bandwidth Overhead – minimizing the load of the additional information used to implement the handoff.
- Triggering times – determining the exact time to trigger handoffs in a wireless channel. It is important to predict when a MS disconnects with BS.

The vertical handoff process can also be divided in three phases: i) Handoff Initiation: in this phase usable networks and available services information is gathered; ii) Handoff decision: it is also called network selection. During this phase, the handoff algorithm determines which network the MS should choose based on multiple parameters; iii) Handoff execution: connections are re-routed to new network in a seamless way.

Even though vertical handoff has the same basic principles of handoff discussed till now, it also deals with other factors that must be considered in handoff decision phase for effective network usage [106]. The parameters used for handoff decision can be listed as follows: (1) network parameters including coverage, bandwidth, load balancing, latency, RSS, SIR, monetary cost, security, connection time; (2) terminal parameters: velocity, battery, wireless interfaces; (3) user preferences: profile, the cost (billing plans), current user conditions; (4) service capabilities and QoS. According to [112]–[114], handoff decision can be classified as follows:

i) Decision function-based strategies. The decision cost function is a measurement of the benefit obtained by handoff to a particular network. Each network that could provide user with services is evaluated with a sum of weighted functions of specific parameters such as traffic load, RSS. These strategies estimates dynamic network conditions including a waiting period before handoff to ensure the handoff is necessary

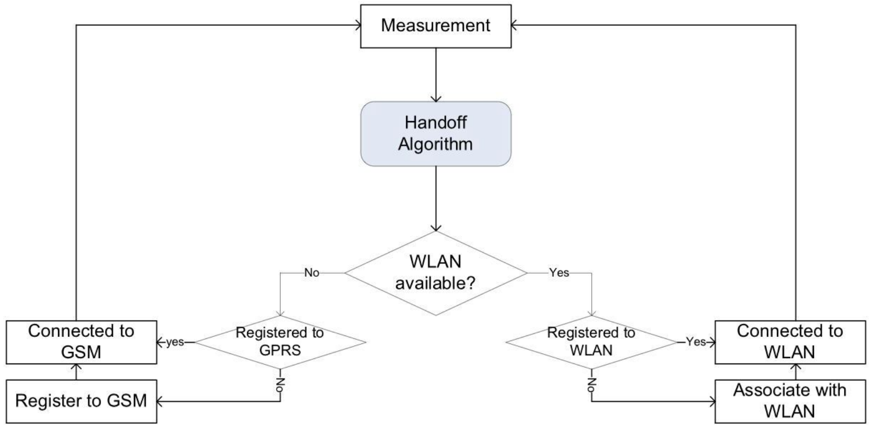


Fig. 13. Handoff between WLAN and GPRS

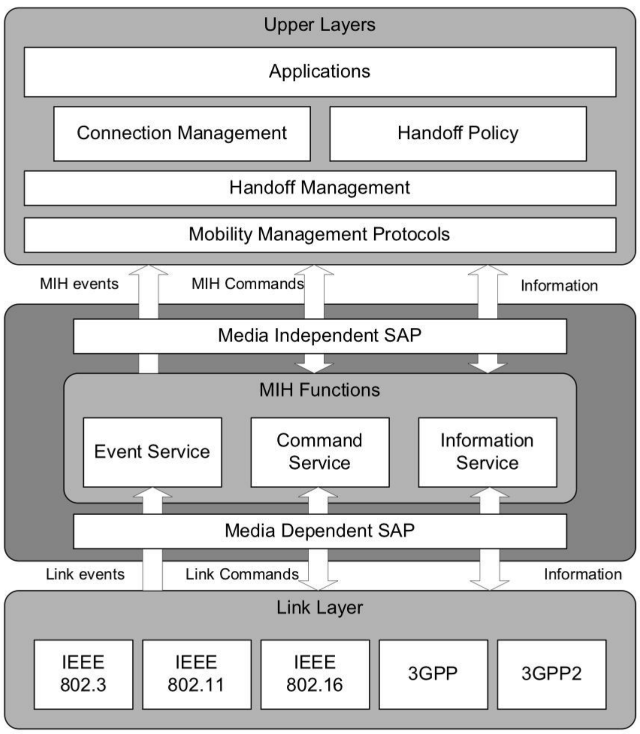


Fig. 14. IEEE 802.21 general architecture

for each MS. The first research in 1999 [115] is policy-enable vertical handoff between LAN and GSM in Mobile IP infrastructure including testbed. Other studies in [116], [117] present the evaluation of these decision strategies between two types of networks: WLAN and GSM/GPRS. Different from the previous methods, these methods in [118], [119] take into account the user preferences in terms of cost and QoS. A cost function is modeled from the user point of view, such as their needs (cost and QoS) and user satisfaction (their willingness to pay the bill).

ii) Multiple attribute decision strategies based on different criteria such as bandwidth, delay, jitter to choose the best appropriate network. Popular methods are: (1) Simple Additive Weighting (SAW): choosing a network based on a weighted sum of all attribute values, (2) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS): the target network is the best network between the ideal solution and the worst solution,(3) Analytic Hierarchy Process (AHP): divide the network selection problem into many sub-problems and assign a weight value to each sub-problem, (4) Grey Relational Analysis (GRA) scores the candidate networks and selects the highest score network. All four methods are present in [121]. In this research, AHP is used to determine the weights for the rest methods and gives a comparison of SAW, TOPSIS and GRA where GRA has a slightly higher bandwidth and lower delay than SAW and TOPSIS for interactive traffic classes.

iii) Fuzzy logic and neural network based vertical handoff. When a large number of imprecise inputs are used, it is usually very difficult to develop analytical formulations of handover decision processes. Fuzzy logic and neural networks are used to process parameters such as RSS, low cost, optimum bandwidth. Applications of fuzzy logic for vertical handoff decision making are given in [94], [109]–[111].The fuzzy decision algorithm in [109] uses the different signals between the current BS and the target BS for vertical handoff between WLAN and GSM. [110] applies bandwidth based fuzzy logic algorithm combined with traffic information and the speed of the MS to handoff between WLAN and WMAN. The combination of fuzzy logic and context information such as price, traffic, sojourn time, seamlessness is presented in [111].The research in [94] has used handoff factor that is mentioned in the previous Section. In [120], neural network is used for finding the best network based on user preferences such as cost, and power. It is shown that the average performance of the neural network selection is 87%.

iv) Context-aware based vertical handoffs uses the knowledge of the context information of the MS and the networks to make a handoff decision between two networks. Context information, which is a criteria for making decision handoff, includes the capacity of the mobile terminal, the user's profile, the network's capacity (QoS, coverage, bandwidth), and the service. In [122]–[124], proposed vertical handoff decision algorithms are based on AHP. [122] stores context information in one repository including the user information, location and traffic. The flexible software-like scheme minimizes the handoff decision time. In [123], the context repository gathers, manages and evaluates the context information; also smart decision mechanisms are proposed. [124] proposes a mobile-initiated and controlled handoff algorithm using context information to process for each service.

In [114], vertical handoffs is classified into four classes: RSS based, bandwidth based, cost function based and combination algorithms. [113] has surveyed several vertical handoff algorithms. Vertical handoff can be implemented in two solutions: i) Network layer vertical handoff solutions based on IPv6 or Mobile IPv4, and ii) Upper layer vertical handoff solutions implement a session layer such as Stream Control Transmission Protocol (SCTP), making connection changes at underlying layers. For more details, the readers are referred to [112]–[114]

A. IEEE 802.21 MIH

The availability of multiple mobile broadband access technologies requires the service providers providing the uses the ability of roaming between different interfaces. The IEEE 802.21 Media Independent Handover standard (IEEE 802.21 MIH) [125] address that requirement by enabling handoff between IEEE 802 networks and non-IEEE 802 networks through a defined media independent handover framework. MIH service access points (MIH SAPs) has been defined as a media independent interface common to all technologies. MIH Function (MIHF) is independently designed as a medium layer between the link layer and the upper layers in the protocol stack of both the MS and the network elements (Fig.14). MIHF enhances the handoffs across heterogeneous access networks, i.e. vertical handoff, and to optimize the session continuity during handoff. MIHF consists of three services [126]:

i) Media Independent Event Service classifies, filters events, Link events and MIH events. Link events are generated within the link layer and received by MIHF. Events that are propagated by the MIHF to the MIHF users are called MIH Events. Link events propagated to upper layers become MIH events. Upper layers can register for an MIH event notification.

ii) Media Independent Command Service allows MIHF to query link resources and help in managing and controlling link behavior related to handoffs by using a set of commands. It also enables both network-initiated and mobile-initiated handoff.

iii) Media Independent Information Service provides a mechanism for an MIH entity to access the fundamental information about neighboring networks, network technology, and available services for handoff process.

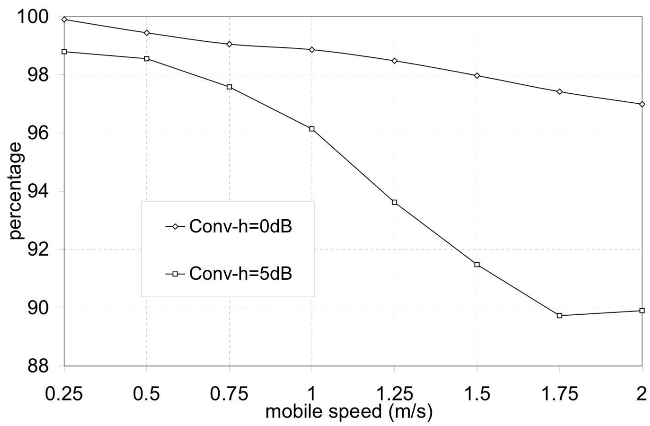
With many of its advantages, the IEEE 802.21 is expected to play an important role in the near future. It does not attempt to standardize the actual handoff mechanism. However, it provides only the overall framework; the actual algorithms to be implemented are left to the designers. To fill this gap, several vertical handoff decision algorithms have been proposed and analyzed. The numerical analysis in [128] shows that the proposed MIH framework reduces handoff latency. [131] proposes the vertical handoff between WiMAX and LTE based on MIH interface. In [127], the handoff scenario between WiMAX and WLAN networks and handoff scenario between 3G and WiMAX networks are present. Handoff between UMTS and WLAN using IEEE 802.21 standard performs well in terms of handoff delay and packet losses [129]. The 802.21 based network-initiated handoff mechanism between UMTS and WiMAX is given in [130]. A seamless handoff between WLAN and WMAN based on IEEE 802.21 and fuzzy logic has been proposed in [132].

VI. Discussions on Handoffs in 60 GHz radio

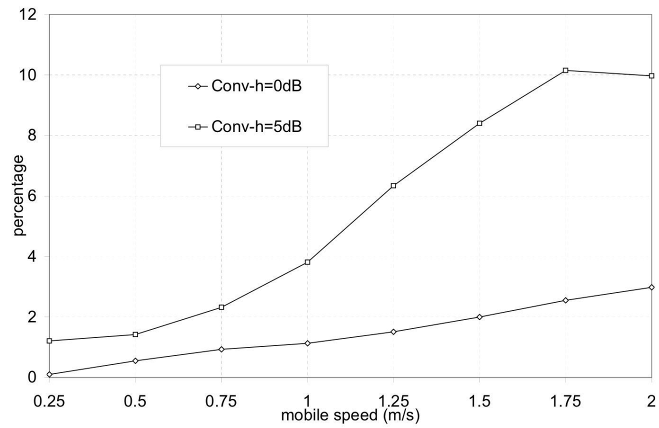
As mentioned above, the target applications of 60 GHz systems have high bandwidth with high required-QoS. 60 GHz systems have small overlapping area where handoff is carried out. Hence, triggering handoffs, completing handoffs in a short time and reducing unnecessary handoffs are very important. Before discussing handoffs in the 60 GHz band, we show the simulation of conventional handoffs in 60 GHz.

The C++ simulation program for 60 GHz in [133] has been modified and enhanced. In this tool, two propagation models are included: two-ray propagation model and free-space as well as using the coverage generated by Radiowave Propagation Simulator (RPS) [134]. In this simulation study, we evaluate the performance of conventional handoffs in terms of the number of handoffs, and the number of unnecessary handoffs. The cell range is 20 m, the velocity of an MS is in the range from 0.25 m/s to 2 m/s. Two-ray propagation model is used. The movement of the MS is modeled using Random Walk Mobility Model with reflection. In the first case, the velocity of the MS is 1 m/s and the overlapping area is set such that it would be enough to complete a handoff. When the hysteresis h is 0 dB, there are 25,687 initiations of handoffs, out of which there are 15,912 unnecessary handoffs. This means that more than 61% handoffs are not necessary. In second case, the overlapping area is as small as 5 m. The simulation results are presented in Fig. 15. Fig. 15(a) and Fig. 15(b) show the percentage of successful handoffs and the percentage of failure handoffs versus the mobile speed for two hysteresis levels, 0 dB and 5 dB. For the hysteresis of 0 dB and increasing the speed of the MS from 0.25 m/s to 2 m/s, the percentage of successful handoffs sinks from 99.9% to 97%, and the percentage of failure handoffs increases from 0.01% to 2.8%. The percentage of successful handoffs significantly drops from 98.6% to 89.9% in case the hysteresis is 5 dB. This means that the delay in handoff increases. The number of handoffs per call and the percentage of ping-pong handoffs in case of 0 dB hysteresis are much higher than those for the hysteresis of 5 dB as shown in Fig. 15(c), and Fig. 15(d).

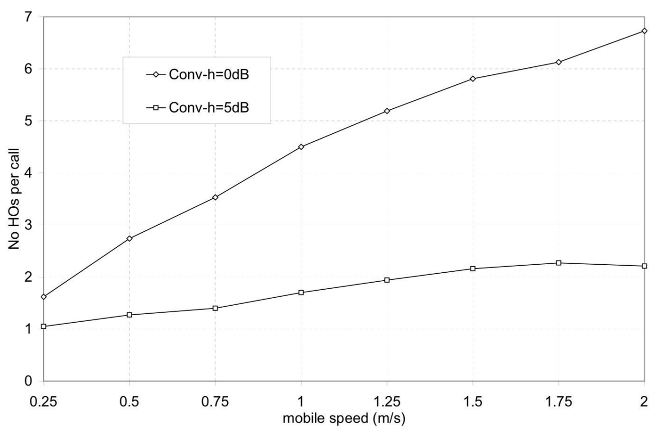
The simulation results show that if the hysteresis is small, the number of unnecessary handoffs is high. If the hysteresis is set high, the number of unnecessary handoffs is low. But it increases the handoff delay, and reduces the number of successful handoffs. Thus traditional handoff algorithms with fixed threshold or fixed hysteresis are not suitable for 60 GHz indoor environment. In order to keep the number of handoffs and the handoff delay as small as possible, the adaptive threshold or hysteresis should be applied. Aforementioned, AI technologies, game theory, fuzzy logic, neural network prediction, and pattern recognition can help in this situation. Handoff algorithms based on these technologies not only reduce the number of handoffs, but also reduce the latency of handoff process. Thus these advantages of the intelligent handoff algorithms can match effectively the required precision in handoffs for 60 GHz based systems.



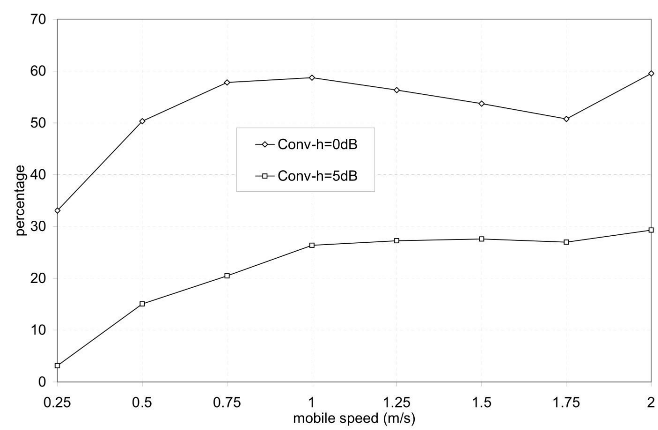
(a) The percentage of successful handoffs



(b) The percentage of failure handoffs



(c) The average number of handoffs per call



(d) The percentage of pingpong handoffs

Fig. 15. The simulation results of conventional handoffs in 60 GHz

Next, with the same hysteresis, the number of successful handoffs depends on the velocity of a MS. A handoff can fail because of a fast moving MS. One thing we should mention is the corner effect. In cellular communication, a fast handoff algorithm is proposed to solve this problem [36]. Due to the propagation characteristic of 60 GHz, SIR can dramatically drop from 20 dB to -5 dB and rise up to 15 dB within a few centimeters [4]. In this case, fast handoffs might not be good solution. This requires that the handoff algorithms must deal with these quick changes, and shadowing problems. As discussed above, the velocity adaptive handoff algorithms and direction-based handoff algorithms also perform well in this situation. Especially in the indoor environment at 60 GHz, the corner effect is more critical since overlapping area exists only in open areas such as doors. Thus it is better to use additional information of a MS such as velocity, direction, and location for making a handoff decision. Using multiple thresholds according to the velocity of the MS, handoff algorithm also operates well in terms of the forced termination and call blocking probabilities [87].

Besides the movement of a MS, the cell size and the overlapping area are also important factors affecting handoff in 60 GHz system. Thus, improving the overlapping area is also a good solution. To do that, “Extended Cell” in [11] and Virtual Cellular Network [6] can help. However, defining when and how to form an EC is still a question while designing such networks. Moving Extended Cell [76] and Moving Cell in [13] can avoid handoffs by moving together with the MS. All above concepts should be incorporated in the applications namely the outdoor directional networks such as highway or train communication and also in the indoor networks where there are many people moving around.

Next, it is possible to improve handoff algorithms by appropriate handoff schemes and resource management. Effective resource allocation schemes such as tuning MAC protocol are also good ways to solve handoff issues of 60 GHz radio. Chess Board MAC protocol proposed in [74] shows that the resource allocation can help make the handoff process successful and fast. By predicting a handoff of an MS or using AI technologies, we can know the target base station and reserve resources for that MS. This would reduce the handoff delay as well as optimize the resource management.

Finally, vertical handoff could also be carried out to improve handoffs in the multi standards 60 GHz systems. [2] shows that the future home networks using the 60 GHz band can provide the users with a variety of bandwidth-level services based on multi technologies like GSM, WLANs, Bluetooth. This means that the appropriate vertical handoff schemes between the above technologies can be a key for solving handoff issues in 60 GHz networks. In [77], a decision algorithm of vertical handoff from 60 GHz radio to WLAN is a good solution when the 60 GHz LOS link is blocked. As discussed, vertical handoff algorithm based on IEEE 802.21 MIH may be applicable in the fourth generation networks where 60 GHz is an obvious candidate.

VII. CONCLUSIONS

We first gave an overview of the handoff algorithms in cellular and wireless network. We later studied the characteristics of 60 GHz bands. The 60 GHz band with its vast unlicensed spectrum of 5 GHz is an obvious choice to support high speed multimedia applications in indoor environment in future. However, its small cell size and steep signal degradation makes handoff a difficult task. Thus we observe more number of handoffs and lesser time for carrying out a handoff. Thus handoff is an important aspect in such indoor network. In this paper, handoff algorithms for cellular wireless communication are investigated first. Conventional handoff algorithms are simple, and easy to deploy. But it shows poor performance in 60 GHz. Intelligent handoff algorithms, which use additional information such as velocity, direction, and traffic information and advanced techniques like fuzzy logic, could get better performance with respect to both the number of handoffs and the handoff delay. They may be complex while deploying, but it is possible to use advanced systems taking support from deployed sensor networks. Using additional information and intelligent handoff algorithms are the keys for successful handoffs in 60 GHz systems. Besides tuning handoff algorithms, we can improve the performance of handoff algorithms through designing the appropriate network architecture. Finally, some recommendations and discussions presented in this paper can help in selecting the right handoff algorithm while designing 60 GHz systems.

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REFERENCES

[1] Cisco, "Scaling the mobile Internet," White Paper, 2009.
[2] Z. Gene et al., "Home networking at 60 GHz: challenges and research issues," *IFIP Int. Federation for Inform. Process.*, vol. 256, pp. 51-68, 2007.
[3] *Handbook of wireless networks and mobile computing,* John Willey & Sons Inc., 2002.
[4] M. Flament, "Propagation and interference issues in a 60 GHz mobile network," in *Proc. 2nd Personal Computing and Commun. Workshop*, Sweden, 1999, pp. 59-64.
[5] G. Filippo et. al., "Mobile and personal communications in the 60 GHz band: a survey," *Wireless Personal Commun.*, vol. 10, no. 2, pp. 207-243, 1999.
[6] M. Flament and A. Svensson, "Virtual cellular networks for 60 GHz wireless infrastructure," in *Proc. IEEE Int. Conf. on Commun.*, vol. 2, 2003, pp. 1223-1227.
[7] K. Sato et al., "Millimeter-wave high-speed spot communication system using Radio-Over-Fiber technology," *IEICE Trans. Electron.*, vol. E88-C, no. 10, pp. 1932-1938, 2005.
[8] L. Rakotondrainibe et al., "Indoor channel measurements and communications system design at 60 GHz," in *Proc. 29th General Assembly of Union Radio-Scientifique Internationale,* Chicago, USA. 2008.
[9] L. Caetano and S. Li, "Benefits of 60 GHz: right frequency, right time," White paper, SiBEAM, Nov. 2005.
[10] L. Jian et al., "A design concept for a 60 GHz wireless in-flight entertainment system," in *Proc. 68th IEEE Veh. Technology Conf.,* Fall 2008, pp. 1-5.
[11] B. L. Dang et al., "Radio-over-Fiber based architecture for seamless wireless indoor communication in the 60 GHz band," *Elsevier Comput. Commun.,* vol. 30, no. 18, 2007, pp. 3598-3613.
[12] O. Andrisano et al., "Impact of cochannel interference on vehicle-to-vehicle communications at millimeter waves," in *Proc. Singapore ICCS/ISITA '92. 'Commun. on the Move',* vol. 2, 1992, pp. 924-928.
[13] L. Bart et al., "Radio-over-fiber-based solution to provide broadband internet access to train passengers [Topics in Optical Commun.]," *IEEE Commun. Mag.,* vol. 45, no. 2, pp. 56-62, 2007.
[14] G. Anzic et al., "A study of 60 GHz intersatellite link applications," in *Proc. IEEE Int. Conf. on Commun.,* Boston, USA, 1983.
[15] S.W. Wang and I. Wang, "Effects of soft handoff, frequency reuse and non-ideal antenna sectorization on CDMA system capacity," in *Proc. 43rd IEEE Veh. Technology Conf.,* 1993, pp. 850-854.
[16] J. Diederich and M. Zitterbart, "Handoff prioritization schemes using early blocking," *IEEE Commun. Surveys & Tutorials,* vol. 7, no. 2, pp. 26-45, 2005.
[17] C. Chen Nee et al., "Integrated dynamic radio resource management," in *Proc. 45th IEEE Veh. Technology Conf.,* vol. 2, 1995, pp. 584-588.
[18] C. Chen-Nee and R.D. Yates, "Evaluation of a minimum power handoff algorithm," in *Proc. 6th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun., 'Wireless: Merging onto the Inform. Superhighway',* vol. 2, 1995, pp. 814-818.
[19] K. Hoon-ki and J. Jae-il, "A mobility prediction handover algorithm for effective channel assignment in wireless ATM," in *Proc. IEEE Global Telecommun. Conf.,* vol. 6, 2001, pp. 3673-3680.
[20] B. Epstein and M. Schwartz, "Reservation strategies for multi-media traffic in a wireless environment," in *Proc. 45th IEEE, Veh. Technology Conf.,* vol. 1, 1995, pp. 165-169.
[21] W. Hailiang et al., "On handoff performance for an integrated voice/data cellular system," in *Proc. 13th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun.,* vol. 5, 2002, pp. 2180-2184.
[22] H. Yieh-Ran et al., "Performance analysis for voice/data integration on a finite-buffer mobile system," *IEEE Trans. Veh. Technol.,* vol. 49, pp. 367-378, 2000.
[23] K. Pahlavan et al., "Handoff in hybrid mobile data networks," *IEEE Personal Commun.,* vol. 7, no. 2, pp. 34-47, 2000.
[24] P. Marichamy et al., "Overview of handoff schemes in cellular mobile networks and their comparative performance evaluation," in *Proc. 50th IEEE Veh. Technology Conf.,* vol. 3, 1999, pp. 1486-1490.
[25] H. Daehyoung and S.S. Rappaport, "Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and nonprioritized handoff procedures," *IEEE Trans. Veh. Technol.,* vol. 35, pp. 77-92, 1986.
[26] L. Xiaoyuan et al., "A dynamic channel pre-reservation scheme for handoffs with GoS guarantee in mobile networks," in *Proc. IEEE Int. Symp. on Comput. and Commun.,* 1999, pp. 404-408.
[27] P. Ramanathan et al., "Dynamic resource allocation schemes during handoff for mobile multimedia wireless networks," *IEEE J. Sel. Areas Commun.,* vol. 17, 1999, pp. 1270-1283.
[28] Z. Yi and L. Derong, "An adaptive algorithm for call admission control in wireless networks," in *Proc. IEEE Global Telecommun. Conf.,* vol. 6, 2001, pp. 3628-3632.
[29] C. Ming-Hsing and M.A. Bassiouni, "Predictive schemes for handoff prioritization in cellular networks based on mobile positioning," *IEEE J. Sel. Areas Commun.,* vol. 18, pp. 510-522, 2000.
[30] Z. Xu, et al., "A new adaptive channel reservation scheme for handoff calls in wireless cellular networks," in *Proc. IFIP Conf. Networking,* Italy, 2002, pp. 672-84.
[31] M. Oliver and J. Paradells, "Adaptative reservation mechanism for wireless networks," in *Proc. IEEE Int. Workshop on Mobile Multimedia Commun. (MoMUC),* Korea, 1997, pp. 55-59.
[32] S. Choi and K. G. Shin, "A comparative study of bandwidth reservation and admission control schemes in QoS-sensitive cellular networks," *Wireless Networks,* vol. 6, no. 4, pp. 289-235, 2000.
[33] W. S. Soh and H. S. Kim, "Dynamic guard bandwidth scheme for wireless broadband networks," in *Proc. IEEE Conf. Comput. Commun. (IEEE Infocom),* USA, 2001, pp. 572-81.
[34] D.J. Goodman, "Trends in cellular and cordless communications," *IEEE Commun. Mag.,* vol. 29, no. 6, pp. 31-40, 1991.
[35] M. Gudmundson, "Analysis of handover algorithms [microcellular radio]," in *Proc. 41st IEEE Veh. Technology Conf., Gateway to the Future Technology in Motion,* 1991, pp. 537-542.

[36] A.E. Leu and B.L. Mark, "Modeling and analysis of fast handoff algorithms for microcellular networks," in *Proc. 10th IEEE Int. Symp. on Modeling, Analysis and Simulation of Comput. and Telecommun. Syst.,* 2002, pp. 321-328.

[37] N. Zhang and J.M. Holtzman, "Analysis of handoff algorithms using both absolute and relative measurements," *IEEE Trans. Veh. Technol.,* vol. 45, pp. 174-179, 1996.

[38] M.D. Austin and G.L. Stuber, "Velocity adaptive handoff algorithms for microcellular systems," *IEEE Trans. Veh. Technol.,* vol. 43, pp. 549-561, 1994.

[39] G. Edwards and R. Sankar, "A predictive fuzzy algorithm for high performance microcellular handoff," in *Proc. IEEE Global Telecommun. Conf.,* vol. 982, 1997, pp. 987-990.

[40] S. Akhila and M. Lakshminarayana, "Averaging mechanisms to decision making for handover in GSM," in *32rd World Academy of Sci., Eng. and Technology,* 2008.

[41] F. Cotes et al., "Multi-valued logic handoff algorithm for cellular systems," in *Proc. 18th Int. Conf. of the North American on Fuzzy Inform. Process. Society,* 1999, pp. 655-659.

[42] *Wireless LAN Medium Access Control (MAC) and physical layer (PHY) specifications,* IEEE 802.11 Standard, 2007.

[43] L. Chung-Sheng et al., "A neighbor caching mechanism for handoff in IEEE 802.11 wireless networks," in *Proc. Int. Conf. on Multimedia and Ubiquitous Eng.,* 2007, pp.48-53.

[44] *Recommended practice for multi-vender access point interoperability via an inter-access point protocol access distribution systems supporting IEEE 802.11 operation,* IEEE 802.11f Standard, 2003.

[45] C.-M. Huang and J.-W. Li, "An accelerated IEEE 802.11 handoff process based on the dynamic cluster chain method," *Elsevier Comput. Commun.,* vol. 30, no. 6, 2007, pp. 1383-1395.

[46] A. Majlesi and B.H. Khalaj, "An adaptive fuzzy logic based handoff algorithm for interworking between WLANs and mobile networks," in *Proc. 13th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun.,* vol. 5, 2002, pp. 2446-2451.

[47] W. Chiapin and L. Tsungnan, "A neural network based adaptive algorithm for multimedia quality fairness in WLAN environments," in *Proc. IEEE Int. Conf. on Multimedia and Expo,* 2006, pp. 1233-1236.

[48] C. Chi-Yuan et al., "Using fuzzy logic to mitigate IEEE 802.11 handoff latency," in *Proc. 14th IEEE Int. Conf. on Fuzzy Syst.,* 2005, pp. 37-42.

[49] M. Portoles et al., "IEEE 802.11 link-layer forwarding for smooth handoff," in *Proc. 14th IEEE Personal, Indoor and Mobile Radio Commun.,* vol. 2, 2003, pp. 1420-1424.

[50] W. Lan et al., "Integration of SNR, load and time in handoff initiation for wireless LAN," in *Proc. 14th IEEE Personal, Indoor and Mobile Radio Commun.,* vol. 3, 2003, pp. 2032-2036.

[51] S.I. Ali and H. Radha, "Hierarchical handoff schemes over wireless LAN/WAN networks for multimedia applications," in *Proc. Int. Conf. on Multimedia and Expo,* vol. 2, 2003, pp. 545-548.

[52] R. Hsieh et al., "S-MIP: a seamless handoff architecture for mobile IP," in *Proc. Twenty-Second Annu. Joint Conf. of the IEEE Comput. and Commun. IEEE Soc.,* vol. 3, 2003, pp. 1774-1784.

[53] R. Hsieh et al., "Performance analysis on hierarchical Mobile IPv6 with fast-handoff over end-to-end TCP," in *Proc. IEEE Global Telecommun. Conf. GLOBECOM,* vol. 3, 2002, pp. 2488-2492.

[54] C. Perkins, IP Mobility Support for IPv4, RFC 3344, IETF, August. 2002

[55] D. Johnson et al., "Mobility Support for IPv6," RFC 3775, IETF, 2004.

[56] *Radio Resource Control (RRC) protocol specification,* 3rd Generation Partnership Project; Technical Specification Group RAN, 3GPP TS 25.331, 2003.

[57] *Radio resource management strategies (Rel. 7),* 3rd Generation Partnership Project; Technical Specification Group RAN, 3GPP TR 25.922, 2007.

[58] H. Holma and A. Toskala, "WCDMA for UMTS - Radio access for third generation mobile communications," John Wiley & Sons, Inc., 2001.

[59] G. Lampropoulos et al., "Handover management architectures in integrated WLAN/cellular networks," *IEEE Commun. Surveys & Tutorials,* vol. 7, no. 4, 2005, pp. 30-44.

[60] N. Vulic et al., "Integration of broadband and broadcasting wireless technologies at the UMTS radio access level," in *Inform. Networking. Towards Ubiquitous Networking and Services: Springer Berlin/Heidelberg,* vol. 5200, 2008, pp. 265-274.

[61] N. Vulic et al., "Quantitative comparison of resource management strategies in UMTS-WLAN integration at the radio access level," in *Proc. 14th IEEE Symp. on Commun. and Veh. Technology in the Benelux,* 2007, pp. 1-5.

[62] B. Andrew, *"Verizon Completes LTE Data Calls,"* [Online 2009-08-18]. Available: http://www.wirelessweek.com/News-Verizon-LTE-Data-Calls-081709.aspx.

[63] *E-UTRA and E-UTRAN Overall Description:Stage 2 (Release 8),* 3rd Generation Partnership Project, 3GPP TS 36.300 v.8.4.0, Mar 2008.

[64] A. Racz et al., "Handover performance in 3GPP Long Term Evolution (LTE) systems," in *Proc. 16th IST Mobile and Wireless Commun. Summit,* 2007, pp. 1-5.

[65] M. Anas et al., "Performance analysis of handover measurements and Layer 3 filtering for Utran LTE," in *Proc. IEEE 18th Int. Symp. on Personal, Indoor and Mobile Radio Commun.,* 2007, pp.1-5.

[66] *3GPP System to Wireless Local Area Network(WLAN) Interworking; System Description (Release 7),* 3rd Generation Partnership Project, 3GPP TS 23.234 v7.5.0, 2007.

[67] K. Kyungmin et al., "A seamless voice call handover scheme for next generation cellular network," in *Proc. 15th Asia-Pacific Conf. on Commun.,* 2009, pp. 782-785.

[68] *Quality of Service,* 3rd Generation Partnership Project, 3GPP S1-99306, May 1999.

[69] *IEEE standard for local and metropolitan area networks–Part 16: air interface for fixed broadband wireless access systems,* IEEE Standard 802.16, 2004.

[70] *IEEE standard for local and metropolitan area networks–Part 16: air interface for fixed and mobile broadband wireless access systems,* IEEE Standard 802.16e, 2005.

[71] S. Ray et al., "Handover in mobile WiMAX networks: the state of art and research issues," *IEEE Commun. Surveys & Tutorials,* vol. 12, no. 3, 2010, pp. 376-399.

[72] C. Sik et al., "Fast handover scheme for real-time downlink services in IEEE 802.16e BWA system," in *Proc. 61st IEEE Veh. Technology Conf.,* vol. 3, 2005, pp. 2028-2032.

[73] WiMAX Forum, *WiMAX Deloyments Maps.* [Online 22-04-2010]. Available: http://www.wimaxmaps.org/

[74] K. H. Bong and A. Wolisz, "Performance evaluation of a MAC protocol for radio over fiber wireless LAN operating in the 60-GHz band," in *Proc. IEEE Global Telecommun. Conf.,* 2003, vol. 5, pp. 2659-2663.

[75] K. H. Jong and J.P. Linnartz, "Virtual cellular network: a new wireless communications architecture with multiple access ports," in *Proc. 44th IEEE Veh. Technology Conf.,* vol. 2, 1994, pp. 1055-1059.

[76] N. Pleros et al., "A moving extended cell concept for seamless communication in 60 GHz radio-over-fiber networks," *IEEE Commun. Lett.,* vol. 12, no. 11, 2008, pp. 852-854.

[77] W. Jing et al., "Solving the incertitude of vertical handovers in heterogeneous mobile wireless network using MDP," in *Proc. IEEE Int. Conf. on Commun.,* 2008, pp. 2187-2192.

[78] N. Jianxia et al., "Directional neighbor discovery in 60 GHz indoor wireless networks," in *Proc. 12th ACM Int. Conf. on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM),* Spain, Oct. 2009, pp. 365-373.

[79] H.-C. Ji et al., "Cost-effective radio-over-fiber systems employing phase-modulated downlink and intensity-modulated uplink," in *Proc. Conf. on Optical Fiber Commun.- incudes post deadline papers,* San Diego, 2009, pp. 1-3.

[80] K. H. Bong et al., "A radio over fiber network architecture for road vehicle communication systems," in *Proc. 61st IEEE Veh. Technology Conf.,* vol. 5, 2005, pp. 2920-2924.

[81] Z. Fan, "Wireless networking with directional antennas for 60 GHz systems," in *Proc. 14th European Wireless Conf.,* 2008, pp. 1-7.

[82] C. D. Gavrilovich, "Broadband communication on the highways of tomorrow," *IEEE Commun. Mag.,* vol. 39, Apr. 2001, pp. 146-54.

[83] C. Plenge and H. Hussmann, "Handover algorithms for cellular communication systems using 60 GHz," in *Proc. 6th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun.,'Wireless: Merging onto the Inform. Superhighway',* 1995, pp. 1057.

[84] N. D. Tripathi, "Generic adaptive handoff algorithms using fuzzy logic and neural networks," PhD thesis, Virginia Polytechnic Institute and State Univ., 1997.

[85] J. P. Mkel, "Effects of handoff algorithms on the performance of multimedia wireless networks," PhD thesis, Faculty of Tech. of the Univ. of Oulu, 2008.

[86] P. Marichamy and S. Chakrabarti, "On threshold setting and hysteresis issues of handoff algorithms," in *Proc. IEEE Int. Conf. on Personal Wireless Commun.,* 1999, pp. 436-440.

[87] K. Young-Il et al., "Analysis of multi-level threshold handoff algorithm," in *Proc. IEEE Global Telecommun. Conf.,'Commun.: The Key to Global Prosperity,* vol. 2, 1996, pp. 1141-1145.

[88] M.D. Austin and G.L. Stuber, "Direction biased handoff algorithms for urban microcells," in *Proc. 44th IEEE Veh. Technology Conf.,* vol. 1, 1994, pp. 101-105.

[89] Z. Li et al., "Position location and direction assisted handoff algorithm in DWCS," in *Proc. 15th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun.,* vol. 1, 2004, pp. 663-666.

[90] Y. Kinoshita and T. Itoh, "Performance analysis of a new fuzzy handoff algorithm by an indoor propagation simulator," in *Proc. 43rd IEEE Veh. Technology Conf.,* 1993, pp. 241-245.

[91] H. Maturino-Lozoya and K. W. Cattermole, "Multiple criteria for hand-off in cellular mobile radio," *IEE Proc. F of Commun., Radar and Signal Process.,* vol. 134, no. 1, 1987, pp. 85-88.

[92] N.D. Tripathi et al., "An adaptive direction biased fuzzy handoff algorithm with unified handoff candidate selection criterion," in *Proc. 48th IEEE Veh. Technology Conf.,* vol. 1, 1998, pp. 127-131.

[93] G. Edwards and R. Sankar, "Hand-off using fuzzy logic," in *Proc. IEEE Global Telecommun. Conf.,* vol. 1, 1995, pp. 524-528.

[94] Y. Nkansah-Gyekye and J.I. Agbinya, "Vertical handoff decision algorithm for UMTS-WLAN," in *Proc. 2nd Int. Conf. on Wireless Broadband and Ultra Wideband Commun.,* 2007, pp. 37-37.

[95] G. Liodakis and P. Stavroulakis, "A novel approach in handover initiation for microcellular systems," in *Proc. 44th IEEE Veh. Technology Conf.,* vol. 3, 1994, pp. 1820-1823.

[96] D. Munoz-Rodriguez et al., "Neural supported hand off methodology in micro cellular systems," in *Proc. 42nd IEEE Veh. Technology Conf.,* vol. 1, 1992, pp. 431-434.

[97] R. Suleesathira and S. Kunarak, "Neural network handoff in shadow-Rayleigh fading," in *Proc. IEEE Int. Symp. on Circuits and Syst.,* vol. 5, 2005, pp. 5146-5149.

[98] H. Maturino-Lozoya et al., "Pattern recognition techniques in handoff and service area determination," in *Proc. 44th IEEE Veh. Technology Conf.,* vol. 1, 1994, pp. 96-100.

[99] K.D. Wong and D.C. Cox, "A pattern recognition system for handoff algorithms," *IEEE J. Sel. Areas Commun.,* vol. 18, no. 7, pp. 1301-1312, 2000.

[100] K.D. Wong and D.C. Cox, "Two-state pattern-recognition handoffs for corner-turning situations," *IEEE Trans. Veh. Technol.,* vol. 50, no. 2, pp.354-363, 2001.

[101] S.S.C. Rezaei and B.H. Khalaj, "Grey Prediction Based Handoff Algorithm," in *Proc. of World Academy of Science, Engineering and Technology 2,* Jan. 2005.

[102] V. Kapor et al., "Handoff criteria for personal communication networks," in *Proc. IEEE Int. Conf. on Commun., Conf. Record, 'Serving Humanity Through Commun.',* vol. 3, 1994, pp. 1297-1301.

[103] L. Ching-Hung and Y. Chun-Jie, "An intelligent handoff algorithm for wireless communication systems using grey prediction and fuzzy decision system," in *Proc. 2004 IEEE Int. Conf. on Networking, Sensing and Control,* vol. 1, 2004, pp. 541-546.

[104] Y. Kinoshita et al., "Advanced handoff control using fuzzy inference for indoor radio system," in *Proc. 42nd IEEE Veh. Technology Conf.,* vol. 2, 1992, pp. 649-653.

[105] N.D. Tripathi et al., "Pattern classification based handoff using fuzzy logic and neural nets," in *Proc. 1998 IEEE Int. Conf. on Commun.,* vol. 3, 1998, pp. 1733-1737.

[106] P. Goyal and S. K. Saxena, "A dynamic decision model for vertical handoffs across heterogeneous wireless networks," in *Proc. World Academy of Science, Engineering and Technology 41,* July 2008.

[107] M. Stemm and R. Katz, "Vertical handoffs in wireless overlay networks," *Springer J. of Mobile Networks and Applications,* vol. 3, pp. 335-350, 1998.

[108] K. Pahlavan et al., "Handoff in hybrid mobile data networks," *IEEE Personal Commun.,* vol. 7, no. 2, pp. 34-47, 2000.

[109] L. Cheng-Jian et al., "An adaptive fuzzy predictor based handoff algorithm for heterogeneous network," in *Proc. 2004 IEEE Annu. Meeting Fuzzy Inform.,* vol. 2, 2004, pp. 944-947.

[110] N. Jing et al., "A bandwidth based adaptive fuzzy logic handoff in IEEE 802.16 and IEEE 802.11 hybrid networks," in *Proc. 2007 Int. Conf. on Convergence Inform. Technology,* 2007, pp. 24-29.

[111] A. Ezzouhairi et al., "A fuzzy decision making strategy for vertical handoffs," in *Proc. 2008 Canadian Conf. on Elect. and Comput. Engineering,* 2008, pp. 583-588.

[112] K. Meriem et al., "An overview of vertical handover decision strategies in heterogeneous wireless networks," *Elsevier Comput. Commun.,* vol. 31, no. 10, pp. 2607-2620, 2008.

[113] A. Sgora and D. Vergados, "Handoff prioritization and decision schemes in wireless cellular networks: a survey," *IEEE Commun. Surveys & Tutorials,* vol. 11, no. 4, pp. 57-77, 2009.

[114] X. Yan et al., "A survey of vertical handover decision algorithms in Fourth Generation heterogeneous wireless networks," *Comput. Networks* vol. 54, no. 11, pp.1848-1863, 2010.

[115] H. J. Wang et al., "Policy-enabled handoffs across heterogeneous wireless networks," in *Proc. Second IEEE Workshop on Mobile Computing Syst. and Applications,* 1999, pp. 51-60.

[116] Z. Fang and J. McNair, "Optimizations for vertical handoff decision algorithms," in *Proc. 2004 IEEE Wireless Commun. and Networking Conf.,* vol. 2, 2004, pp. 867-872.

[117] W. Shen and Q.A. Zeng, "A novel decision strategy of vertical handoff in overlay wireless networks," in *Proc. 5th IEEE Int. Symp. on Network Computing and Applications,* 2006, pp. 227-230.

[118] H. Izumikawa et al., "User-centric seamless handover scheme for realtime applications," in *Proc. 18th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun.,* 2007, pp. 1-5.

[119] O. Ormond et al., "Utility-based intelligent network selection in beyond 3G systems," in *Proc. IEEE Int. Conf. on Commun.,* vol. 4, 2006, pp. 1831-1836.

[120] N. Nasser et al., "Middleware vertical handoff manager: a neural network–based solution," in *Proc. 2007 IEEE Int. Conf. on Commun.,* 2007, pp. 5671-5676.

[121] E. Stevens-Navarro and V.W.S. Wong, "Comparison between vertical handoff decision algorithms for heterogeneous wireless networks," in *Proc. 63rd IEEE Veh. Technology Conf.,* 2006, pp. 947-951.

[122] Q. Wei et al., "Context-aware handover using active network technology," *Computer Networks,* vol. 50, no. 15, 2006, pp. 2855-2872.

[123] S. Balasubramaniam and J. Indulska, "Vertical handover supporting persative computing in future wireless networks," *Elsevier Science of Computer Commun.,* vol. 27, no. 8, pp. 708-719, 2004.

[124] T. Ahmed et al., "Architecture of a context-aware vertical handover decision model and its performance analysis for GPRS - WiFi handover," in *Proc. 11th IEEE Symp. on Comput. and Commun.,* 2006, pp. 795-801.

[125] *Media Independent Handover Services,* IEEE Standard P802.21/D14.0, Sept. 2008.

[126] A. De La Oliva et al., "An overview of IEEE 802.21: media-independent handover services," *IEEE Wireless Commun.,* vol. 15, no. 4, pp. 96-103, 2008.

[127] K. Taniuchi et al., "IEEE 802.21: Media independent handover: features, applicability, and realization," *IEEE Commun. Mag.,* vol. 47, no. 1, pp.112-120, 2009.

[128] K. Moon et al., "A study on IEEE 802.21 MIH frameworks in heterogeneous wireless networks," in *Proc. 11th Int. Conf. on Advanced Commun. Technology,* 2009, pp. 242-246.

[129] P. Machan et al., "Performance of mobility support mechanisms in a heterogeneous UMTS and IEEE 802.11 network offered under the IEEE 802.21 standard," in *Proc. 1st Int. Conf. on Inform. Technology,* 2008, pp. 1-4.

[130] B. Joo-Young et al., "Network-initiated handover based on IEEE 802.21 framework for QoS service continuity in UMTS/802.16e networks," in *Proc. IEEE Veh. Technology Conf.,* 2008, pp. 2157-2161.

[131] S. Jae-Han and C. Jong-Moon, "IEEE 802.21 MIH based handover for next generation mobile communication systems," in *Proc. 4th Int. Conf. on Innovations in Inform. Technology,* 2007, pp. 431-435.

[132] Y. Shun-Fang and S. Jung, "A IEEE 802.21 handover design with QOS provision across WLAN and WMAN," in *Proc. 2008 Int. Conf. on Commun., Circuits and Syst.,* 2008, pp. 548-552.

[133] B.L. Dang et al., "Performance study of a novel architecture for indoor networks at 60 GHz using extended cells," in *Proc. 4th IEEE Consumer Commun. and Networking Conf.,* 2007, pp. 17-22.

[134] Actix Radioplan product, *Radiowave propagation simulator (RPS).* [Online]. Available: http://www.actix.com/radioplan_rps/

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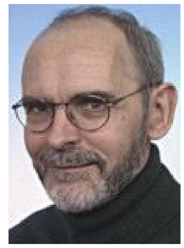

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