Solving Incertitude of Vertical Handovers in Heterogeneous Mobile Wireless Network

Jing Wang R. Venkatesha Prasad I.G.M.M. Niemegeers
CWPC-WMC/IRCTR, Delft University of Technology,
Mekelweg 4, 2628CD Delft, The Netherlands
jing.wang@tudelft.nl, {vprasad,ignas.n}@ewi.tudelft.nl

ABSTRACT

Wireless communication network is evolving towards more heterogeneous with rapid emergence of new radio technologies. 60GHz radio relying on line-of-sight (LOS) transmission is one of the promising solutions to support in-door high quality multi-media applications. Due to the vulnerable nature of LOS links, *vertical handover*, by switching the mobile device to the backup WLAN system from 60GHz radio, is critical to support a seamless session. However vertical handover for short LOS blocking events degrade perceived quality of the media due to frequent switching. In this paper, we propose a cognitive approach to solve incertitude during vertical handover. We first present an overview of our proposed cognitive network architecture, and further under this framework we introduce and examine via simulations a decision algorithm based on decision theory. Our algorithm takes into account multiple factors such as user preference, network situation, device capability and effect of environment. We show its ability to effectively make handover decision in uncertain situations. The method and results herein are applicable, in general, to any other situation where such a decision is to be made.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—Wireless Communication

General Terms

Algorithms, Performance, Design.

Keywords

Cognitive network architecture, 60GHz radio, Heterogeneous network, Session mobility, Decision Theory, Vertical handover decision algorithm

1. INTRODUCTION

With the increasing demand on sustained high data rate to sufficiently support the transport of multiple high quality multimedia streams such as uncompressed HDTV signals, the attention of the research community now has been on the higher frequency bands. As advocated by Smulders [1] a promising solution is the license-free 60GHz band where bandwidth is abundant. With this resource it is foreseen that network capacity can be tremendously increased compared to the current wireless LAN technologies. Data rates in the order of Gbps are feasible in this band.

60GHz radio is intended to provide connection for very high data rate within a short distance, mainly in the in-door environment. To save transmission power while ensuring satisfactory link quality at high data rates, a directional antenna configuration is recommended for the system to conserve energy and to combat multipath effects [2]. Besides, line-of-sight (LOS) propagation has been one of the requirements for 60GHz radio. Experimental results in [2] show that more than $10dB$ degradation is observed for non-LOS links when both transmission and receiving antennas have omni-directional configurations. Severer degradation is thus expected while using directional antennas. However LOS propagation is difficult to be guaranteed especially in the in-door environment with many potential obstructions due to human activities and other objects in the environment. In heterogeneous network environment where multiple radio systems are overlapped, this problem can be solved by switching the communication session from one radio system to another in a seamless manner, i.e., the so-called vertical handover, to keep the continuity of the session running on top.

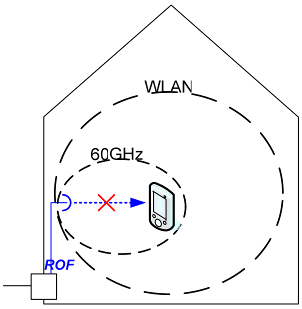


Figure 1. In-door Radio Links

A typical scenario is presented in Fig.1, where both 60GHz radio cell and WLAN cell are formed and are overlapping inside the building via Radio-over-Fibre (RoF) technology [3]. 60GHz radio cell has smaller diameter due to the short transmission range. For multimedia content distribution, streaming via 60GHz LOS link is always a preferable option as high data rate can be supported and better perceptible quality is offered for real-time multimedia streaming. If the LOS link is blocked, a strong degradation in the

WICON 2007, October 22-24, Austin, USA

DOI 10.4108/wicon.2007.2099

perceived quality is very likely. However, the LOS blocking is a temporary phenomenon usually lasting for a short period. Nonetheless on a few occasions it can last for many seconds. Therefore, it is necessary to switch in some cases and in other cases not. In fact switching back and forth will cause additional degradation. Thus it is critical for the system to make a decision to handover in time. That is, whether to switch to the backup WLAN for streaming multimedia content under reduced quality, or to wait without switching -- hoping that this disturbance, being a transient, will wane away in a short time. If LOS link recovers faster with the possible short blocking duration the “waiting” action results in saving unnecessary switching. However, if the outage of the link is relatively long then the “switching” action may avoid session braking down. Thus the goal is to minimize perceptible quality degradation and make a well informed decision to switch between the available links.

It has always been challenging for networks and/or nodes being able to solve such issues as described in this novel 60GHz radio communication scenario, which hasn’t been thoroughly examined. Due to dynamic and random nature of occurrences of blocking and taking into account many other subjective and objective factors such as humans, network, devices, etc, this kind of uncertain and complex situation are fuelling the need for sophisticated networking approaches and decision algorithms. The concept of Cognitive Network [4] is inspired by the idea of Knowledge Plane for the Internet [5]. Cognitive network is able to identify operational problems and goals centered on its users’ need and to manage on its own to solve these problems in the heterogeneous, distributed and dynamic network environment. Therefore our work is motivated to seek a solution based on cognitive approach in order to invoke network intelligence. First we present here a broader view of our proposed cognitive network architecture, with elaborating the design of its essential part – the Cognitive Module (CM). Further under this framework we introduce and examine via simulations a *Decision Theory* based algorithm specific to making decision whether or not to handover communication session from the radio system being interrupted to an alternative system, say from 60GHz radio to WLAN in this particular scenario. Without loss of generality, our proposed cognitive approach can be potentially applicable to any handover decision-making between the available radio systems when severe link quality deterioration is detected. Further, this type of *incertitude* can be seen in many situations, for example, while selecting a route in a network of frequently failing paths. We believe that this study can be modeled so as to suit various situations with a slight modification. Thus we strive here to give a completely generalized solution, not only from the algorithm perspective, but also from architecture point of view, which provides further extensibility to the system.

The rest of the paper is organized as follows. Section 2 gives an overview of earlier researches on vertical handover decision-making. Section 3 introduces the cognitive network architecture with the functionality and interaction of its basic components. Our decision algorithm is presented in Section 4, where the vertical handover decision-making task is modeled into a decision theory problem. Section 5 shows the detailed simulation setup, with the simulation results being presented and discussed in Section 6. In Section 7 we conclude and discuss our future plans.

2. EARLIER STUDIES

Traditionally, vertical handover decisions are simply based on comparison of different radio systems in terms of link level performance indicators such as Signal-to-Noise Ratio (SNR) and/or signal strength and network level performance indicators such as throughput, traffic load etc. In [6] authors comparably examined four algorithms – the Load Balancing Algorithm (LBA), the Coverage Threshold Algorithm (CTA), the Rate Maximizing Algorithm (RMA) and the Theoretical Circuit Switched Equivalent Algorithm (TCA). They show through simulations that by including further information location of the users, the handover performance can be greatly improved.

Recently more sophisticated decision algorithms, based on Artificial Intelligence (AI) techniques, have been used in order to handle and exploit more relevant factors from users, networks, devices and environment for better vertical handover strategies. A vertical handover algorithm based on fuzzy control theory [7] considers multiple criteria such as information about the load, velocity of mobile terminal and a set of rules defined from prior knowledge. With the similar control principle, a decision algorithm has been proposed in [8] taking into account power levels of received signals, cost of operation for particular network and amount of unused bandwidth. In [9] vertical handover problem is formulated as a Markov decision process, where a link reward function and a signaling cost function are introduced to evaluate actions. In [10] a context-aware decision algorithm based on Analytic Hierarchy Process (AHP) is designed considering both static and dynamic context at the user terminal and the network.

However what has been missing in these studies is a comprehensive networking architecture to systematically support the algorithm specific solutions. In [11] and [12], handover decision algorithms have been regarded as handover policies and accommodated into policy-based network architectures, which basically follow the IETF’s policy model as in [13]. However, as argued in [14] policy-based solutions specify exactly what to do in certain situations based on predefined policies, and hence are lacking in flexibility and extensibility compared to a “more intelligent” cognitive approach, which aims at enabling network “self-” actions automatically and adaptively according to the users and situations. Therefore, we propose to solve incertitude of vertical handover through a decision algorithm under cognitive network framework. For this specific problem our decision theory based algorithm is able to take into account multiple factors and make use of information such as user preference, network situation, device capability and environment situation. The cognitive approach provides a basic structure for networks being able to derive and access the information, and being able to identify various complex network operation problems and adopt sophisticated algorithms to solve those problems.

3. COGNITIVE APPROACH

3.1 Cognitive Network Architecture Overview

Inspired by the idea of constructing a knowledge plane for the Internet [5], we propose to add in a new plane, Cognitive Plane (CP) to the prevailing three-plane (i.e. data-, control- and management planes) network architecture to enable network sophistication. This makes our cognitive networking approach distinct from the other recent researches such as [4] and [19]. The former proposed to implement software agent alike cognitive elements with a three-layer architecture inspired by the common model of cognition. The latter divided the network into separate data and control planes, and implemented the set of functions to support cognitive networking in the control plane. These approaches either did not clearly address how the cognitive functions interacting with the existing functions in data- control- and management planes, or rose the potential complexity for a major modification of the functions based on the existing plane division. The advantage of bringing in a separate CP is two-fold. Firstly, it can minimize the modification of the current control and management functions. Secondly, it allows network preventing failure of cognitive functions by switching back to the original non-cognitive control and management functions.

We identify three functional modules in CP: knowledge module, cognitive module and executive module as shown in Fig.2. This identification is inspired by the structure of *intelligent agent* from the field of AI [18].

Knowledge module perceives environment and collects meta-information - the percepts from the users, the network, and the environment in which the network operates. The aggregated percepts are further processed within the knowledge module, where they are converted into *knowledge* – the well-classified and translated information that can be used by the tasks in the cognitive module for decision making. In our particular case, the knowledge includes the information on the blocking events, the network condition, the device capacity and the user input on their satisfaction about the streaming quality under different radio techniques. Further explanation of this four-dimensional knowledge is given in the following section 3.2. *Executive module* takes decisions made from cognitive module and exerts them into actions upon network operation. In this paper, we are not into discussion further about information collection, knowledge derivation and action exertion, rather focus on the core decision-making module within CP, namely the *Cognitive Module* (CM). As depicted in Fig.2, this module has three basic components: CM manager, toolbox of cognitive techniques and a variety of cognitive tasks.

CM manager is the crucial unit of cognitive module. It has an overview of the toolbox in terms of each tool's capability and resource consumption. Based on the needs of the cognitive tasks and the available resources, it should decide how to assign tools for given cognitive tasks. CM manager also needs to take control of all the cognitive tasks, such as task registration control, task status monitoring and so on. Besides CM manager is responsible for establishing communication with the knowledge module -- such as registering the format and type of knowledge to meet the syntax and semantic requirement specified by each cognitive task and cognitive technique. *Toolbox* is the repository of all cognitive techniques which can be applied to make decisions for cognitive tasks. Toolbox registers its resources and takes commands from CM manager. Based on the instructions from the CM manager, toolbox releases instances of its tool-objects to cognitive tasks for solving various problems in network operation. Those problems are registered in CM manager and are formed as dedicated tasks – the *Cognitive Tasks*. Each cognitive task is identified by the problem to be solved and the type of cognitive technique and knowledge to be used. A cognitive task can ask explicitly for certain cognitive technique to solve the problem, and it can also ask CM manager to choose a proper tool for solving it. All the cognitive tasks are kept filed in the CM manager, and they need to report their status to the CM manager from time to time. Output of cognitive task is the decision to be further passed to the Executive Module and exerted into action.

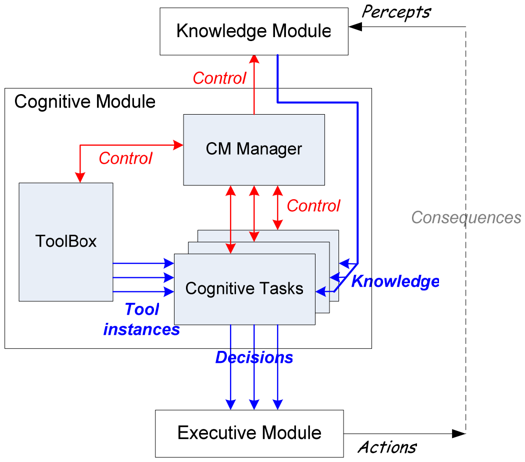


Figure 2. Cognitive Plane Architecture

The dashed line between actions and percepts in Fig.2 implies that the percepts actually contain and are affected by the consequences of actions. Thus design of CP architecture follows a closed loop approach.

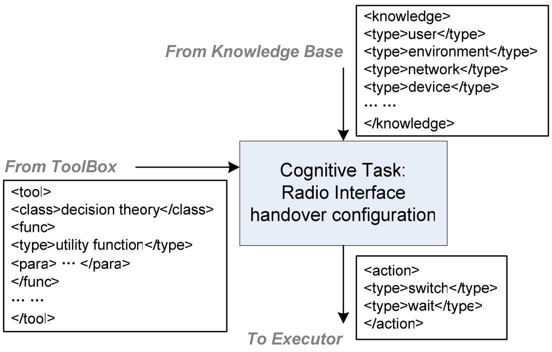


Figure 3. Cognitive Task - Vertical Handover Decision-making

3.2 A Cognitive Task for Solving Incertitude in Vertical Handover

We propose and demonstrate here the use of a specific cognitive task to solve the problem regarding incertitude of vertical handover. Using the proposed cognitive networking architecture, we map the problem onto cognitive module as shown in Fig.3. One cognitive task is created by CM manager to support the whole process of the problem solving. An instance of a selected cognitive technique object is initiated and released to the cognitive task as a tool to solve the problem. The specific cognitive technique used in this case is a decision algorithm based on the utility function as defined in the decision theory by calculating the expected utility (or the expected cost) of each possible action. It assists decision making about the selection of a particular action which has the highest utility or lowest cost. Substantial knowledge transferred from knowledge module into this cognitive task has four dimensions:

1) User preferences describe the user experience of the media content transferred via different radio technologies. It is typically represented as scores on the lines of ITU-T's Mean Opinion Score (MOS) [15], which is found by the ranking given by users to quantitatively indicate his/her favor on one radio system over another.

2) Environment situation, in this case, is the knowledge about frequency of blocking events and duration of each of them; this knowledge can be a specific stochastic model of occurrence of blocking events. It can also be the prediction of the duration of individual blocking event via certain learning algorithms.

3) Network situation is represented by the switching time from one radio system to another. The switching time is highly influenced by the factors such as the number of users within the radio system, the traffic load, the link quality and so on. It is the sum of two activities – (a) the actual time to configure the device into the target radio network, mainly the time for network association and network address allocation; (b) the time for session level handshake to enable the session to be carried out via a different radio system.

4) Device capability mainly deals with the resources. Here availability of the buffer is considered as the representative of this aspect keeping in mind the multimedia streaming application. For convenience, buffering time is used to describe the display duration of the buffered multimedia data.

This knowledge is used by the decision algorithm to further generate the expected utility of the possible consequent states under each action. A decision of whether to switch to the backup WLAN system or wait till 60GHz LOS link recovery is made at the occurrence of each blocking event. Here we do not delve into the collection of information which is an integral part of the knowledge but the decision to be made once we have some knowledge about the situation.

4. DECISION ALGORITHM

4.1 Decision Algorithm Principle

The proposed decision algorithm is based on *Decision Theory* [16], which has been used in intelligent agents to make a decision to select an action from several alternatives under uncertain situations. In our case, uncertainty is due to the lack of knowledge of the precise duration of each blocking event. The fundamental idea of decision theory is to choose the action that yields the highest expected utility averaged over all the possible outcome of the action. In our particular case it is to select an action, i.e., to switch or wait when 60GHz LOS link is blocked. The decision making should evaluate the utility of the consequent states led by each action, that is, the decision is to take the action a^* such that,

$$a^* = ArgMax_{a_i \in A} \sum_{Sij \in S} P_{ij} U(S_j) , \qquad (1)$$

Here, $U(S_j)$ is the utility of state S_j , which is the consequent state of action a_i with probability P_{ij} .

Instead of utility per se, one can also make decisions based on the utility difference between each possible consequent state and the ideal state, where no blocking happens and it is able to always use the preferred 60GHz LOS link with high bandwidth. This difference reflects perceptible degradation judged by the media viewer when 60GHz LOS is blocked. We choose the action which brings the smallest difference, in other words lowest degradation. Therefore, we re-write Eq.1 into Eq.2, and use $\Delta U(S_j)$ to represent the utility difference (or utility degradation).

$$a^* = ArgMin_{a_i \in A} \sum_{Sij \in S} P_{ij} \Delta U(S_j) , \qquad (2)$$

Based on Eq.2, our proposed decision algorithm consists of following five basic steps to reach a decision in any decision-making situation.

Step 1. Identify the knowledge (information) about the user, network, device and physical environment, and define decision-making situation.

Step 2. Define the consequent state transitions under each action.

Step 3. Calculate the probability of the consequent states under each action, and the utility difference of each consequent state.

Step 4. Calculate the total expected utility degradation of each action by summing up the utility difference of each consequent state scaled with the probability of this state.

Step 5. Compare the expected utility degradation of all the actions. The action with the smallest degradation is selected.

Before further elaborating these steps in the subsequent sub-sections, we make certain assumptions as stated below:

- All the 60GHz LOS connections have similar channel quality and gives same perceptible experience. Further, it assumed to be the same for WLAN.
- When the device using 60GHz radio interface, WLAN interface is deactivated to conserve power; while using WLAN connection (When 60GHz LOS is blocked), 60GHz interface is still active. In this way the device can be immediately informed and it may switch back to 60GHz radio system whenever the blocking wanes away and 60GHz LOS link is available.
- The stochastic model of the blocking events or prediction of blocking duration is available from knowledge module by using certain learning algorithms.

4.2 Decision-making Situation[1]

---

[1] The term is defined in decision theory to specify the agent's knowledge about the environment, the agent's assessment as to its possible courses of action, the possible results of the actions and desirability of these results [16].

To describe the decision-making situation and to calculate the expected utility of each state, a quadruple is defined as given below [16].

$$D = < P_c(S), A, proj, U > .$$

U stands for Utility, which quantifies the user experience when media stream delivered through different radios. The value of the utility can be assigned directly based on the user's ranking, or by simply taking the MOS-like values given by the user. Since the decision-making is asserted by evaluating the expected state utility led by the actions, tying user's opinion to the utility assignment reflects that decisions are ultimately made upon the user's experience. Here we define utility density u , which represents the utility value per time unit.

$$u = \begin{cases} u_{60}, & \text{streaming through 60GHz radio system} \\ u_w, & \text{streaming through WLAN system} \\ u_z, & \text{losing connection, no streaming and} \\ & \text{display is interrupted} \end{cases}$$

It is easy to see that, $u_{60} > u_w > u_z$.

A : $\{a_i\}$ represents a pool of possible actions, in our case, the actions can be a_1 : Switch to WLAN when 60GHz radio is blocked, or a_2 : Wait till the 60GHz link recovers.

$P_c(S)$ is the probability of initial states when making a decision. In our case, the decision is taken only when the 60GHz LOS link is temporally blocked, therefore there is only one initial state S_0 , which is "Lost 60GHz connection" with probability $P_c(S_0) = 1$.

$proj$ stands for projection function, which represents mapping from initial states to each possible consequent state S_j under certain action, that is, $proj(P_c(S), a_i) = P_i(S_j)$, which is represented by P_{ij} in Eq.2. Probability of each consequent state is determined by several factors, such as the blocking event duration (t_{blk}), the buffering time (t_{buf}) and the duration for switching (t_{swt}) between multiple radios (i.e., time for handover or switching time).

4.3 State Transitions

Taking into account blocking duration, buffering time and switching time, we consider four possible consequent states led by the two actions as shown in Fig.4.

S_1 is one of the consequent states under the action "Switch". In this case, switching time is shorter than the buffering time; therefore the multimedia streaming quality has an observable degradation due to switching to use a low speed WLAN link. But there is no discontinuity in multimedia content display because enough content is buffered and can cover the interrupted streaming when switching to different radio systems. As shown in Fig.5(a), at the beginning of the blocking event, 60GHz radio link is interrupted, the system begins the procedure to switch to WLAN system. After a period of t_{swt} , data traffic has been successfully handed over, but data buffered via 60GHz radio system are still displayed with good perceptible quality until all of them are used for the duration of t_{buf} . From that moment, the displayed media content is transmitted via WLAN link until the end of the blocking, and after t'_{swt} the system switches back to 60GHz. After the period of t'_{buf} , finishing buffered data from WLAN, multimedia content via 60GHz radio link is displayed again.

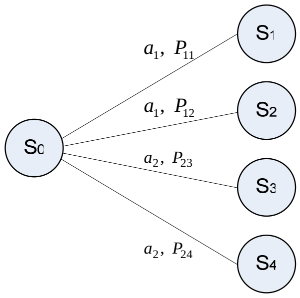


Figure 4. Consequent States under Actions

S_2 is another state among the consequent states under action "Switch". In this case, switching time is longer than the buffering time. Therefore, there is not only observable degradation due to switching to a lower speed link but also a discontinuity in multimedia content display, due to the lack of buffered content to cover the interrupted streaming while switching to a different radio system. From Fig.5(b), we can observe a period of t_z when multimedia content stops playing after finishing the buffered data and before successfully connecting to WLAN system.

S_3 is under the action "Wait". In this case the device has buffered enough data to cover the relatively short blocking duration, as shown in Fig.5(c). Therefore no degradation and no discontinuity js observed while displaying the multimedia content.

S_4 is another consequent state under the action "Wait" where buffering time is not long enough to cover the relatively long blocking event. Thus the content display will be discontinuous since multimedia stream stops after playing out all the buffered data until 60GHz radio recovers. Thus t_z is observed in Fig.5(d)

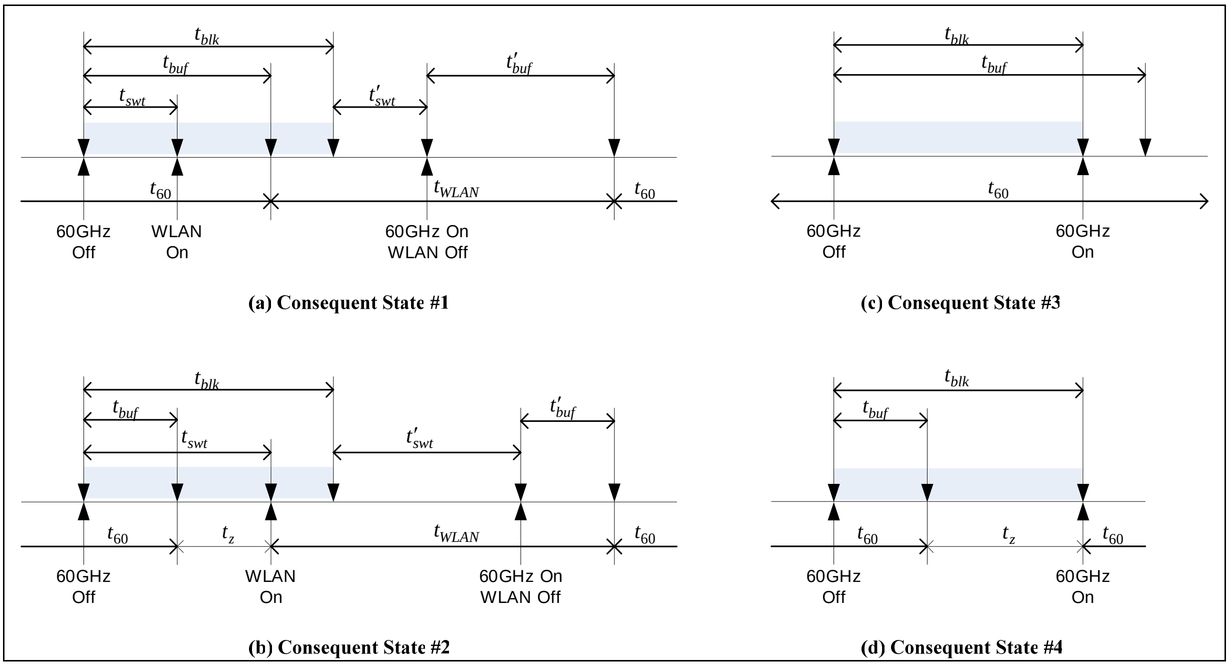
4.4 Utility Degradation Calculation

Based on the above description of the state transitions, the utility functions can be derived as given below. The probability of each consequent state is shown in Eq.3:

$$\begin{cases} P_{11} = \Pr(t_{buf} \geq t_{swt}) \\ P_{12} = \Pr(t_{buf} < t_{swt}) \\ P_{23} = \Pr(t_{buf} \geq t_{blk}) \\ P_{24} = \Pr(t_{buf} < t_{blk}) \end{cases} \text{with} \quad \sum_j Pij = 1 \qquad (3)$$

The utility degradation of each possible consequent states is calculated via Eq.4.

Referring to the time relations shown in Fig.5, we can further write Eq.4 into Eq.5.



(a) Consequent State #1

(c) Consequent State #3

(b) Consequent State #2

(d) Consequent State #4

Figure 5. Time Line of the Consequent States

$$\begin{cases}\Delta U(S_1)=t_{WLAN}\cdot(u_{60}-u_w)\\ \Delta U(S_2)=t_z\cdot(u_{60}-u_z)+t_{WLAN}\cdot(u_{60}-u_w)\\ \Delta U(S_3)=0\\ \Delta U(S_4)=t_z\cdot(u_{60}-u_z)\end{cases}\qquad(4)$$

$$\begin{cases}\Delta U(S_1)=(t_{blk}+t'_{swt}+t'_{buf}-t_{buf})\cdot(u_{60}-u_w)\\ \Delta U(S_2)=(t_{swt}-t_{buf})\cdot(u_{60}-u_z)\\ \qquad\qquad +(t_{blk}+t'_{swt}+t'_{buf}-t_{swt})\cdot(u_{60}-u_w)\\ \Delta U(S_3)=0\\ \Delta U(S_4)=(t_{blk}-t_{buf})\cdot(u_{60}-u_z)\end{cases}\qquad(5)$$

As discussed previously t_{buf} , t'_{buf} , t_{swt} and t'_{swt} are device and system dependent, and it is reasonable to assume that their values can be obtained from the knowledge module with negligible error. As t_{blk} is by nature more random and is difficult to obtain directly hence we use the expectation $E(t_{blk})$ or the predicted value of it.

Therefore, for a_1 and a_2 the expected utility degradations can be formulated as:

$$\begin{cases}\Delta U_{a_1}=P_{11}\cdot\Delta U(S_1)+P_{12}\cdot\Delta U(S_2)\\ \Delta U_{a_2}=P_{23}\cdot\Delta U(S_3)+P_{24}\cdot\Delta U(S_4)\end{cases}\qquad(6)$$

By comparing ΔU_{a_1} and ΔU_{a_2} the action corresponding to the smaller value can be chosen.

5. SIMULATION SETUP

The decision algorithm is implemented in MATLAB. In the simulation we test the algorithm based on two different kinds of information (knowledge in AI terms) on blocking events. Test-A is using blocking events modeled through a random process, and the expectation of blocking duration $E(t_{blk})$ has been used instead of individual blocking duration; while in Test-B we assume certain sophisticated learning algorithm is able to give prediction for the duration of each blocking event, and the predicted values are used in the decision algorithm.

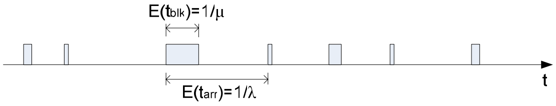


Figure 6. Blocking Event Model

5.1 Setup A

In this test, the independent blocking events are modeled with a Poisson arrival of the exponential inter-arrival rate λ and with exponentially distributed blocking duration with the rate μ (Fig.6). In the simulation, we consider a moderate dynamic environment with fixed $\lambda=1/30s$, and we increase the expectation of blocking duration $E(t_{blk})=1/\mu$ from $1s$ to $10s$ in steps of $1s$ to simulate different blocking traces. When $E(t_{blk})$ is relatively small, say around $2s$, blocking events are mainly led by people walking through 60GHz LOS links with a moderate speed. Higher $E(t_{blk})$ indicates that the blocking events are caused by other factors such as people standing in LOS links for longer time, or devices being behind an obstacle, etc. Buffering time is dependent on the data rate and the maximum buffer size available on the devices. As the link quality may change from time to time, we take the buffering time, t_{buf} and

t'_{buf} randomly between $t_{buf\_\min}$ and $t_{buf\_\max}$. $t_{buf\_\min}$ can be 0 when data is not buffered, and $t_{buf\_\max}$ corresponds to time to display buffered data when reaching the maximum buffering capacity. We assume that the switching time consists of both network configuration and session handshake, which are affected by dynamic network conditions. We set t_{swt} and t'_{swt} randomly between $t_{swt\_\min}$ and $t_{swt\_\max}$. As 60GHz radio system has been proposed to use beacon based device discovery scheme and so does WLAN system, this implies a short network association time in most of the cases. Besides, previous measurements in [17] show that with certain modification SIP based session handshake in IPv6 can be reduced to $< 500ms$. Therefore, it is reasonable to assume $t_{swt\_\min}$ taking around $0.5s$ under favorable network conditions. We vary the boundaries of the buffering time and switching time and examine the decision algorithm under different possible situations. Detailed account of the values of the parameters used is shown in Table.1. As 200 samples with inter-arrival rate at $1/(30s)$ are used for each $E(t_{blk})$, we mean to simulate blocking event occurrence during, for example a movie, of around 100 minutes.

To evaluate the performance of our proposed decision theory based decision algorithm (represented using notation "*d*"), we compare it with other three naive decision algorithms: (1) algorithm "r" - randomly choose an action out of the two, (2) algorithm "s" - always switch to WLAN system on blocking and (3) algorithm "w" – always wait for 60GHz recovery. Further we define a benchmark algorithm, which knows precisely each blocking duration and gives the most optimal choice on the action resulting in the lowest utility degradation. Compared with the actions chosen by the benchmark algorithm, the probability of the correct action is used as the metric to find the performance of all the techniques.

5.2 Test-B Setup

In this second test, we still modeled the blocking event in the same way as in Test-A with exponential inter-arrival time and exponentially distributed blocking duration. However instead of using $E(t_{blk})$ we used the prediction of blocking duration.

In our simulation, the prediction is a set of values manipulated from the set of true values of the blocking durations. Taking into account that the prediction can not always be precise, we introduce errors into the predicted values and generate a prediction which has certain confidence $conf$, with which the error of each predicted value is within certain boundary err. That is with a percentage of $conf$, the predicted blocking duration falls within $\pm err$ error bar of the true blocking duration. In this test, we compare the performance of decision algorithm with respect to different err, which is varied from 10% to 90% in steps of 20%, and we also compared them with the performance of only using $E(t_{blk})$ in decision algorithm. For each simulation we used 200 samples, and the detailed parameter set is as shown in Table.2.

6. RESULTS AND DISCUSSIONS

6.1 Simulation Results of Test-A

Test-A.1 considers the network situation with moderate switching time varying between $0.5s$ and $1.5s$, and the comparable buffering time with the same upper and lower boundaries. Performance of different algorithms is compared as depicted in Fig.7. With the increasing $E(t_{blk})$, in case its value is smaller than $4s$, the "Wait" action is more appropriate than the "Switch" action, while with a larger value, blocking events should be handled by the "Switch" action. Choosing a random action gives round 50% correct results for all $E(t_{blk})$ cases. Our proposed decision algorithm yields in each case the best result. This indicates that by using this algorithm the system is aware of different factors within each situation and make out rational choices to minimize the perceived quality degradation. As shown in Fig.8 and Fig.9, the result that decision algorithm outperforms other three algorithms Test-A.2 and Test-A.3, with the buffering time being increased to around $2.5s$ and $4.5s$ correspondingly.

One observation is that for certain $E(t_{blk})$ the decision algorithm does not perform so well, which is quite obvious in Fig.7 and Fig.8, where performance curve of the decision algorithm has a nadir when $E(t_{blk})$ equaling $4s$ and $7s$. This is because the decision is made based on the comparison between ΔU_{a_1} and ΔU_{a_2}. In our decision algorithm $E(t_{blk})$ is used in place of the true values, therefore this fixed value fails to represent the dynamic nature of the true blocking duration. For different switching times and buffering times, at certain $E(t_{blk})$ the dynamics of blocking duration is specifically critical to determine the result of the comparison between ΔU_{a_1} and ΔU_{a_2}. Therefore, by only using the fixed, expected values it is too generic to derive the precise decisions. Another observation is that with the increase in the buffering time, the "Wait" action being more favorable when $E(t_{blk})$ becomes larger. It is reasonable because longer buffering time is able to cover the blocking events with longer duration without switching to the backup radio system.

In Test-A.4 we considered switching time of $0.5s$ which is a minimal practicable value as explained in simulation setup. At the same time a relatively small buffering time is used. Because the switching time is comparably smaller than the simulated blocking event duration in general, and the buffered data is always not enough to cover the outage in streaming due to the blocked LOS. Thus "Switch" action turns out to be more favorable in most of the cases as shown in Fig.10.

Test-A.5 shows the scenario when the network situation is unfavorable resulting in relatively longer switching time of around $4.5s$. At the same time the device can only offer moderate buffer capability, which is not able to cover the break in streaming due to switching to another radio system. Shown in Fig.11, decision algorithm always chooses to "Wait" considering the high cost of "Switch" delay. But with the increasing $E(t_{blk})$, the number of correct decision is reduced. This is because of higher expected value, which implies that more blocking events with considerably longer duration are likely to happen.

Table 1. Test-A Parameter Setting

	λ	$1/\mu$	$t_{swt\_\min}$	$t_{swt\_\max}$	$t_{buf\_\min}$	$t_{buf\_\max}$
Test-A.1	1/(30s)	1s:1s:10s	0.5s	1.5s	0.5s	1.5s
Test-A.2			0.5s	1.5s	2s	3s
Test-A.3			0.5s	1.5s	4s	5s
Test-A.4			0.4s	0.6s	0	1s
Test-A.5			4s	5s	2s	3s
Test-A.6			0.5s	2s	0	5s

Table 2. Test-B Parameter Setting

	λ	$1/\mu$	*conf*	*err*	$t_{swt\_\min}$	$t_{swt\_\max}$	$t_{buf\_\min}$	$t_{buf\_\max}$
Test-B	1/(30s)	1s:1s:10s	90%	10%:20%:90%	0.5s	2s	0	5s

For longer blocking events it is worth losing a few seconds of content and to switch to continue streaming via low-speed WLAN system. Waiting for the blocking to end makes the session starve for a longer duration without media being played and hence degrades quality severely.

To get a general view of the performance of the decision algorithm, we simulated more scenarios with different buffering and switching times. In Test-A.6, the switching time is randomly chosen from $0.5s$ to $2s$ and the buffering time from $0s$ to $5s$ .Fig.12 shows the result of the simulation that the percentage of the correct action decided by the algorithm remains the highest compared to other algorithms. This indicates that our decision algorithm is able to select best actions on most occasions even without the complete knowledge about the situation, as only expectation instead of true blocking duration is used.

6.2 Simulation Results of Test-B

As discussed above, due to the use of $E(t_{blk})$, the dynamic nature of blocking duration can not be reflected in the decision algorithm. Concerning this point, in Test-B we compared the performance of the decision algorithm that used the predicted blocking duration. As shown in Fig.13 with the increase in the prediction error, the flawed information leads to an incorrect decision under the whole range of blocking duration. But compared to only using $E(t_{blk})$ for making decision, for blocking occurrences with large expectation values the performance degradation is moderate. This is due to the fact that for the cases with large $E(t_{blk})$ it brings in high errors by using expectation. This is because the difference between the expectation and the true value sometimes can be even larger than 90% of the true value, in other words, an error more than 90% of the true value is introduced. The figure also suggests that if the prediction with 90% confidence within 50% error bar can be obtained, it is better to use the prediction rather than the expectation to make a decision.

7. CONCLUSION

In this paper, we have presented a cognitive approach to make vertical handover decisions for, but not restricted to 60GHz radio/WLAN coexisting situation. A novel cognitive architecture is introduced to enable network intelligence, and a handover decision algorithm has been proposed under the cognitive framework. The decision algorithm we proposed is based on the decision theory, which takes into account multiple factors from the users, environment, network and the device. The simulation results show that this sophisticated algorithm gives a better performance on deciding the correct actions in the partial observable and non-deterministic environment. Furthermore, the results indicate the specific situations which limit the effectiveness of the algorithm. Further, we seek to derive and understand this limitation by analytical means. We would also intend to add multiple actions. Instead of hard actions such as “wait”, and “Switch” we try to consider “Wait-and-Switch” actions.

8. ACKNOWLEDGMENTS

We thank Xueli An of WMC, TU Delft for providing valuable information on 60GHz radio. We also thank IOP Future Home Network project and IST Project MAGNET Beyond for funding this work. .

MAGNET Beyond is a continuation of the MAGNET project. MAGNET Beyond is a worldwide R&D project within Mobile and Wireless Systems and Platforms Beyond 3G. MAGNET Beyond will introduce new technologies, systems, and applications that are at the same time user-centric and secure. MAGNET Beyond will develop user-centric business model concepts for secure Personal Networks in multi-network, multi-device, and multi-user environment. MAGNET Beyond has 32 partners from 15 countries, among these highly influential Industrial Partners, Universities, Research Centers, and SMEs. www.ist-magnet.org.

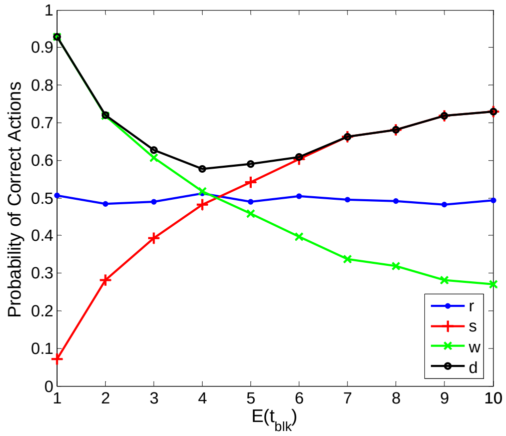


Figure 7. Performance Comparison (Test-A.1)

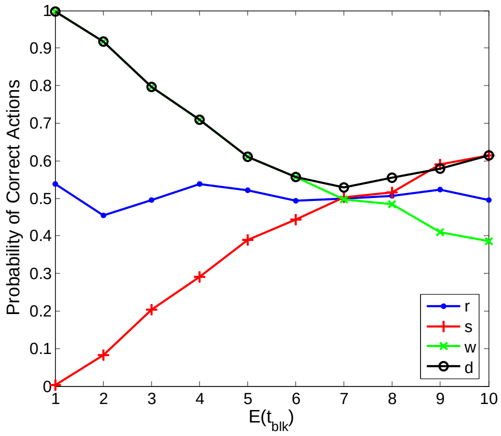


Figure 8. Performance Comparison (Test-A.2)

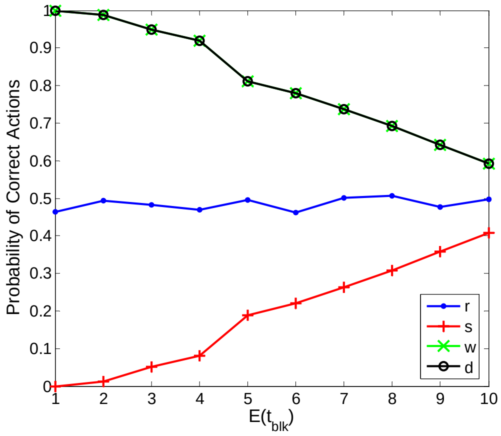


Figure 9. Performance Comparison (Test-A.3)

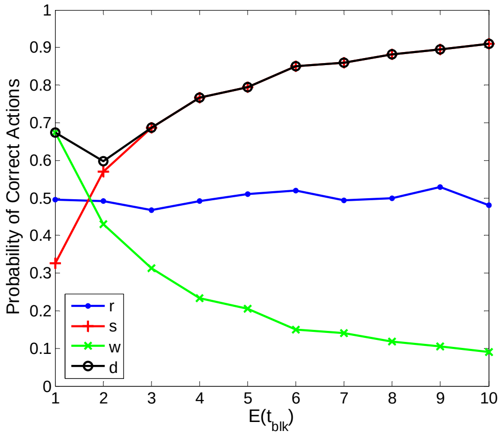


Figure 10. Performance Comparison (Test-A.4)

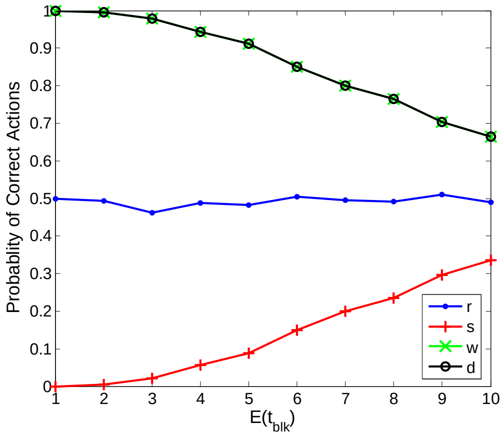


Figure 11. Performance Comparison (Test.A-5)

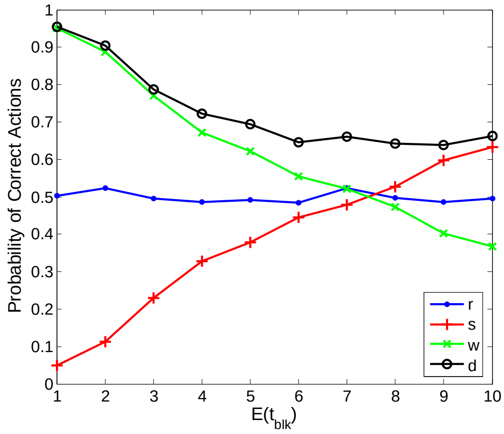


Figure 12. Performance Comparison (Test-A.6)

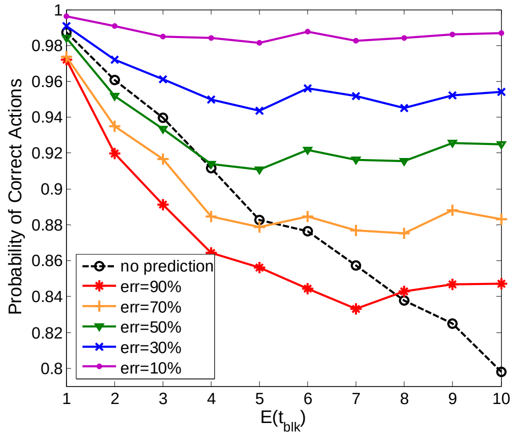


Figure 13. Performance Comparison (Test-B)

9. REFERENCES

[1] P. F. M. Smulders, “60 GHz radio: prospects and future directions”, in Proceedings of IEEE Benelux Symposium Chapter on Communications and Vehicular Technology, Eindhoven, the Netherlands, 2003

[2] H. Yang, H, M. H. A. J. Herben and P. F. M. Smulders, “Frequency selectivity of 60-GHz LOS and NLOS indoor radio channels”, In Proceedings of IEEE Vehicular Technology Conference, Melbourne, Australia, May 2006

[3] B. L. Dang, V. Prasad, I. Niemegeers, M. G. Larrode and A. M. J. Koonen, “Toward a seamless communication architecture for in-building networks at the 60 GHz band”, In Proceedings of the 31st IEEE Conference on Local Computer Networks (LCN2006), Florida, US, November, 2006

[4] R. W. Thomas, D. H. Friend, L. A. Dasilva, and A. B. Mackenzie, “Cognitive networks: adaptation and learning to achieve end-to-end performance objectives”, IEEE Communications Magazine, vol: 44, no: 12, pp: 51-57, Dec. 2006

[5] D. Clark, C. Partridge, C. Ramming, and J. Wroclawski, “A Knowledge Plane for the Internet", ACM SIGCOMM 2003, Karlsruhe, August 2003

[6] V. A. de Sousa, R. A. de O. Neto, F. de S. Chaves, L. S. Cardoso and F. R. P. Cavalcanti, “Access selection with anticipatory vertical handover for multi-access networks”, In Proceedings of IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications, Helsinki, Finland, Sept. 2006

[7] S. Horrich, S. B. Jamaa and P. Godlewski, “Adaptive Vertical Mobility Decision in Heterogeneous Networks”, In Proceedings of Third International Conference on Wireless and Mobile Communications (ICWMC '07), Guadeloupe, French Caribbean, 2007

[8] H. Liao, L. Tie and Z. Du, “A vertical handover decision algorithm based on fuzzy control theory”, In Proceedings of the First International Multi-Symposiums on Computer and Computational Sciences (IMSCCS '06), April 2006

[9] E. Stevens-Navarro, V. W. S. Wong and Y. Lin, “A vertical handoff decision algorithm for heterogeneous wireless networks”, In Proceedings of IEEE Wireless Communications and Networking Conference (WCNC'07), Hong Kong, China, March 2007

[10] T. Ahmed, K. Kyamakya and M. Ludwig, “Design and implementation of a context-aware decision algorithm for heterogeneous networks”, In Proceedings of the 21st Annual ACM Symposium on Applied Computing, Dijon, France, April 2006

[11] G. Nyberg, C. Ahlund and T. Rojmyr, “SEMO: A policy-based system for handovers in heterogeneous networks”, In Proceedings of International Conference on Wireless and Mobile Communications (ICWMC '06), Bucharest, Romania, July 2006

[12] F. Zhu and J. McNair, “Multiservice vertical handoff decision algorithms”, EURASIP Journal on Wireless Communications and Networking, vol. 2006, pp. 1-13, 2006

[13] R. Yavatkar, D. Pendarakis and R. Guerin, “A framework for policy-based admission control”, IETF RFC 2753, January 2000

[14] W. E. Walsh, G. Tesauro, J. O. Kephart and R. Das, “Utility functions in autonomic systems” In Proceedings of IEEE International Conference on Autonomic Computing (ICAC’04), 2004

[15] ITU-T Recommendation P.800, “Methods for subjective determination of transmission quality”, 1996

[16] S. Parsons, et al Ed “Game Theory and Decision Theory in Agent-based System”, Kluwer Academic Publishers, 2002

[17] N. Nakajima, A. Dutta, S. Das and H. Schulzrinne, “Handoff Delay Analysis and Measurement for SIP based mobility in IPv6”, In Proceedings of IEEE International Conference on Communications (ICC '03), Alaska US, May 2003

[18] P. Norvig, S. J. Russell, “Artificial Intelligence – A Modern Approach”, Prentice Hall, 2003

[19] X. Jing and D. Raychaudhuri, “Global Control Plane Architecture for Cognitive Radio Networks”, In Proceedings of IEEE CogNet07, Glasgow, 2007