A solution framework to provide management services for wireless communications in the digital home

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Abstract .- *The future digital home (DH) is envisioned as a place where a plethora of diverse personal and machine-to-machine communications will coexist to support different applications in areas such as information and entertainment, home automation, home health care and home security and management. Wireless technologies are usually the preferred solution to cope with DH communications for their ease of installation and use. However, expected capacity demand and the lack of coordination between an increasing number of diverse wireless devices in use within the DH is seriously challenging the performance and usability of wireless technologies. This article outlines a novel technical solution intended to enhance capacity and quality of DH wireless communications. The proposed solution establishes a radio independent coexistence framework where key operational radio settings of DH devices are co-ordinately determined and new spectrum sources other than traditional ISM bands can be exploited for DH communications. The addressed solution enables a business player to offer management services for DH wireless communications so that ordinary users can be relieved from complex management tasks likely to arise within the DH. The article discusses on potential management service providers that could benefit from the proposed solution. Besides, the functional architecture of the proposed solution together with the set of procedures necessary for the management of the DH wireless communications are outlined. A realistic indoor scenario is presented as an illustrative use case to show how a proper decision making logic managing the DH could improve the efficiency by selecting the most suitable spectrum for in-house wireless communications. Finally, the main implementation issues are identified and discussed in order to outline a feasible roadmap.*

1. Introduction: characterising the digital home

The future digital home (DH) [1] is envisioned as a place where a plethora of diverse personal and machine-to-machine communications will coexist. Users' communication needs in DHs are emerging in many different areas such as information and entertainment, home automation, home health care and home security and management, among others [2]. Hence, the future DH is expected to consist of not only computing devices with communication capabilities (such as desktop PCs, laptops and the likes), but also of consumer electronics (like TV sets with wireless interfaces, digital media servers, camcorders, game consoles, home security and automation systems, etc.), as well as more traditional appliances (such as washing machines, fridges, etc.) equipped also with communication interfaces to enable, e.g., remote control and monitoring.

A set of specific scenarios and use cases that allow quantifying to some extent potential communications requirements in DHs can be found in [3]. As an example, one of the scenarios analyzed in [3] considers the coexistence of five simultaneous application flows in an "evening in family home" scenario: one 20 Mbit/s High Definition (HD) TV streaming flow for the recording of a documentary from a set-top box to a network attached storage (NAS) device; another 20 Mbit/s HD TV streaming flow to watch a TV program in a bedroom screen; one music 0.1-5 Mbit/s streaming flow from a Hi-Fi equipment to wearable headphones; a 50 Mbit/s high quality video streaming from a desktop PC to a large display; and a 30-100 kbit/s Voice over IP (VoIP) call. Hence, aggregated application bit rate for this scenario is close to 100 Mbit/s of "stream" rate-constrained flows. Other scenarios addressed in [3] also consider peak rate requirements of up to 1 Gbit/s for additional non rate-constrained application flows. Furthermore, some prospective research studies [4] indicate that, in order to avoid the risk that in-home communications become the bottleneck for future services, capacity required inside the house should be 5-10 times higher than the bandwidth provided by the broadband access network connection (e.g., considering a broadband access of 100 Mbit/s reaching the house, expected indoor bandwidth would range from 500 Mbit/s to 1 Gbit/s). Therefore, aggregated data rates supported in the DH environment are expected to be above hundreds of megabits per second.

Different technologies may support DH communications. Among them, wireless technologies are usually preferred over wired ones for the ease of installation and use. As a result, the usage of multiple and diverse wireless technologies within households is becoming pervasive. At present and in the near future, existing wireless technologies suitable for solving DH's needs include simple remote controllers, cordless phones, wireless sensor networks (WSNs) such as IEEE 802.15.4 (Zigbee), wireless personal area networks (WPANs) such as IEEE 802.15.1 (Bluetooth) and WiMedia Alliance UWB, and wireless local area networks (WLANs) such as IEEE 802.11 (Wi-Fi). This proliferation of multiple wireless technologies is feeding a growing concern that there are going to be too many incompatible and not interoperable systems and standards in the DH environment.

Besides technological heterogeneity, aforementioned wireless DH technologies mostly rely on the use of the same licence-exempt radio spectrum bands, e.g., Industrial, Scientific and Medical (ISM) bands in 2.4 GHz and 5 GHz. In order to assess the order of magnitude of the achievable capacity in these bands, let's focus on Wi-Fi technologies where 3 and 18 non-overlapping 20 MHz channels are available in the 2.4 GHz and 5 GHz bands respectively. Over those channels, typical data rates that can be effectively achieved with current IEEE 802.11 solutions at a distance of 10 m between peer devices in a home environment are estimated around 10-20 Mbit/s [5]. This leads to an overall achievable capacity about 200-400 Mbit/s that has the same order of magnitude as the DH aggregated data rates foreseen in a single household. Furthermore, when considering neighbouring households with similar communications requirements, effective capacity achievable in each of them is further diminished as a result of mutual interference that precludes the utilization of all channels in a single house. It is also worth noting that worse signal propagation conditions in 5 GHz might also prevent the utilization of this band when end devices are located far away or several walls or floors lie in between. Consequently, the amount of spectrum available in the 2.4 and 5 GHz bands may not suffice to guarantee that communications requirements in future DH scenarios will be squarely accomplished, particularly if quality of service (QoS) has to be provided in scenarios with a high number of coexisting radio systems (e.g., dense urban areas). In order to overcome the aforementioned limitations, the introduction of cognitive radio technologies to improve wireless communications in the DH is increasingly drawing the attention of the research community and business domain. Several European research projects have recently considered this application environment (e.g., ARAGORN [6], OneFIT [7], OMEGA [3]). Also, standardisation bodies dealing with cognitive radio and dynamic spectrum access like ETSI Reconfigurable Radio Systems (RRS), IEEE DySPAN-SC / 802.11af / 802.19.1, ECMA International and IETF PAWS are actually addressing scenarios and use cases related to DH communications [8]-[11]. Indeed, several works [12][13] have already pointed out the business opportunities that the management of the DH creates for various firms (e.g., network operators, software platform firms, specialised management companies, etc.) and the important advantages that network operators can have in the provisioning of these services compared to other potential providers.

In this context, this paper proposes and develops a technical solution framework to manage wireless communications in the DH. The paper provides the identification of involved business players, the definition of a functional architecture in terms of entities, interfaces and basic procedures, the analysis of an illustrative use case to gain insight into the potential benefits of such a solution and a discussion on related standardisation and regulation aspects that are relevant for its implementation. This results in a comprehensive view on the solution framework that, to the best of authors' knowledge, has not been addressed to a similar extent by other related works available in the literature.

The proposal is based on:

1. The introduction of management mechanisms in order to enhance the level of coordination of diverse wireless technologies used within the DH and, consequently, increase the efficiency and capacity achieved for a given amount of spectrum resources. Improved coordination is cornerstone for QoS-guaranteed service provisioning in the DH.
2. The utilisation of cognitive radio technologies that enable a flexible access to new sources of spectrum resources, in addition to currently license-exempt ISM bands, with the corresponding increase in the capacity available for DH communications. For example, radio technologies designed to operate in UHF bands in an opportunistic manner (i.e., TV white spaces) such as the ECMA-392 radio networking standard [10] and the ongoing work in IEEE 802.11af can play a key role in the future DH environment. Likewise, the utilization of licensed spectrum resources for enhancing QoS assurances of some DH connections constitutes an important building block of the proposed solution.
3. The provision of the management services for DH wireless communications by specialised business players, hence relieving ordinary users from such tasks and paving the way for new business models in the near future. This approach is well aligned with current business trends for telecom providers and other firms that see the DH as a promising scenario for the delivery of value-added services [12].

The remainder of the paper is organised as follows. Section 2 introduces the proposed solution to manage wireless communications in the DH and discusses the role that different business players such as mobile operators can undertake in the provision of these management services. Next, the functional architecture of the proposed solution is addressed in Section 3. On this basis, the analysis of an illustrative use case is covered in Section 4 and Section 5 is devoted to elaborating on the implementation aspects. Finally, concluding remarks are drawn in Section 6.

2. Proposed solution: Digital Home Manager for wireless communications

The proposed solution is conceived as a radio technology independent coexistence framework intended to improve wireless communications within the DH environment. The centerpiece of the solution is a new specialized function, referred to as *Digital Home Manager* (DHM). The DHM is intended to assist in setting up relevant operational parameters of DH devices with wireless interfaces, called wireless DH devices for short hereafter. Hence, key radio operational parameters of the wireless DH devices in use throughout the household (e.g., operating spectrum band and frequency channel) are to be remotely controlled by the DHM. Decision making logic for determining suitable configuration parameters follows a given set of operational policies and is fed by relevant context information (e.g., spectrum availability and DH application needs). Decisions are made in an autonomous manner by the DHM without requiring assistance from the end user. Decision making logic can embrace cognitive techniques to enable the DHM to learn, decide and act based on particular household characteristics and users' behaviours.

A business player is expected to take over the responsibility of the operation of the DHM and so become a provider of management services for DH wireless communications. The management of the DH creates new business opportunities for service providers [12] by relieving ordinary users from cumbersome management workload unavoidably linked to the growing complexity of the DH environment. In this case, the proposed coexistence framework consists of an in-home device hosting DHM functions[1] along with a remote Operation, Administration, Maintenance and Provisioning (OAM&P) platform operated by the management service provider and reachable through the home broadband access network connection. This solution approach to provide management services for DH wireless communications is illustrated in Figure 1.

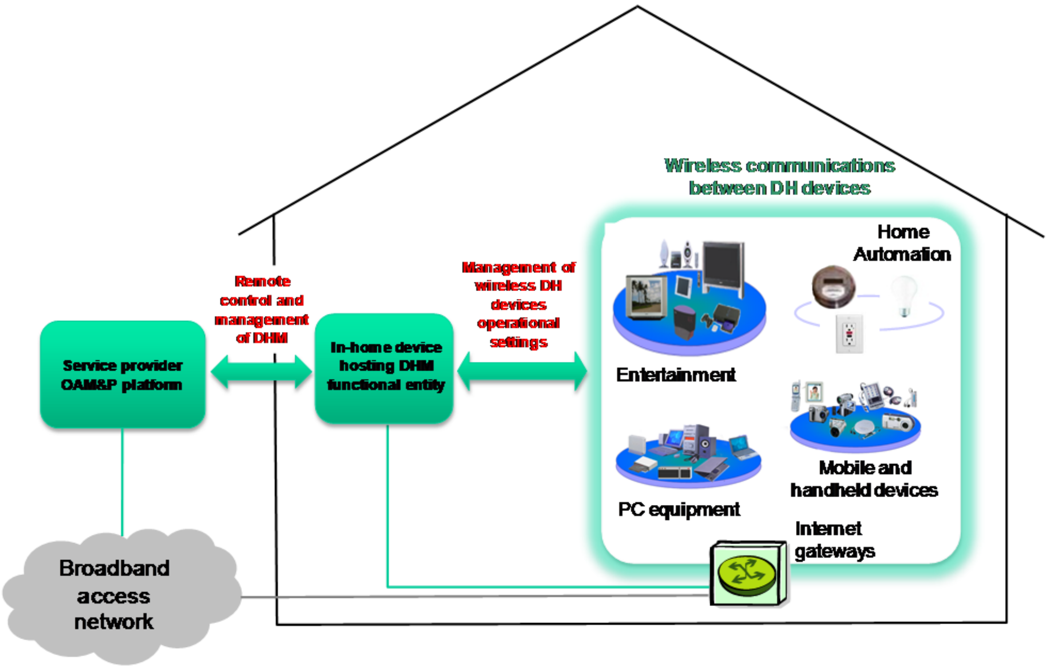

Figure 1. Provisioning of management services for DH wireless communications

DH management is not to be limited to communications issues and may entail multiple and diverse additional aspects such as device installation, software management, security management and multimedia content and data management. There is a great diversity of players from different business sectors that converge in the DH environment and which may come up with a suitable business model to take care of some or all of aforementioned DH management aspects. Thus, broadband access network operators, software platform companies, security or application software providers, media companies and consumer electronics vendors, or mutual interest partnerships established between them, could ultimately benefit from the provisioning of DH management services. Among such potential business players, some business model analyses [12] point out that network operators can play an exceptional role compared to others for providing this sort of services. Raised arguments note that communication services provided by network operators often require the installation of in-home hardware devices (e.g., home gateways[2] by fixed broadband network operators or femtocells[3] by mobile network operators) which are usually offered in a leased regime to users so that the operator has already to take care of the management of these DH devices. Furthermore, within network operators, we anticipate that mobile network operators (MNO) can additionally benefit from the following two key points:

- Expertise in radio planning and optimisation of wireless communications systems can be a key differentiating factor to properly manage technical challenges arisen in DH wireless communications. Synergies with its core business can be exploited.

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[1] DHM functions can be allocated in a special-purpose dedicated device or embedded in a device together with other functionalities needed by the service provider. An example would be the allocation of DHM functions within home gateway devices in the case of access network operators acting as management service providers.

[2] Home Gateway is a device connecting the DH to the Internet and other service platforms.

[3] Femtocells are low-power wireless access points that connect standard mobile devices to a mobile operator's network using residential DSL (Digital Subscriber Line) or cable broadband connections.

- Licensed spectrum owned by MNOs can be of great value for supporting some sensitive or critical DH networking communications and for better supporting and providing QoS in the DH.

Hence, an MNO can become a kind of "integral connectivity" service provider encompassing both outdoor mobility access and management of wireless communications within the DH.

3. Functional architecture and procedures

Figure 2 depicts the functional architecture of the proposed solution to provide management services for DH wireless communications. The architecture is built upon three functional entities:

- Digital Home Manager (DHM), whose main responsibility is to facilitate the coexistence of wireless DH devices by proper decision-making on their operational radio settings as already introduced in previous section.
- Digital Home Client (DHC). This entity is to be embedded inside any wireless DH device intended to be managed by a DHM (i.e. DHC-enabled device). DHC is in charge of configuring the radio interface(s) of the hosting wireless DH device and, for that purpose, it communicates with the DHM in order to provide/obtain the required information.
- Digital Home Support Server (DHSS). This entity is located within the operator's OAM&P platform and interacts with the DHM hosting device through the household broadband access connection. This entity supports the operation of DHM through the provisioning of context information (e.g., spectrum availability in the household area) and suitable operational policies (e.g., technical and operational rules to enforce different configurations). One DHSS entity can serve a number of DHMs and consequently it can facilitate the coordination between neighbouring DHMs (e.g., discovery and connection setup between neighbouring DHMs).

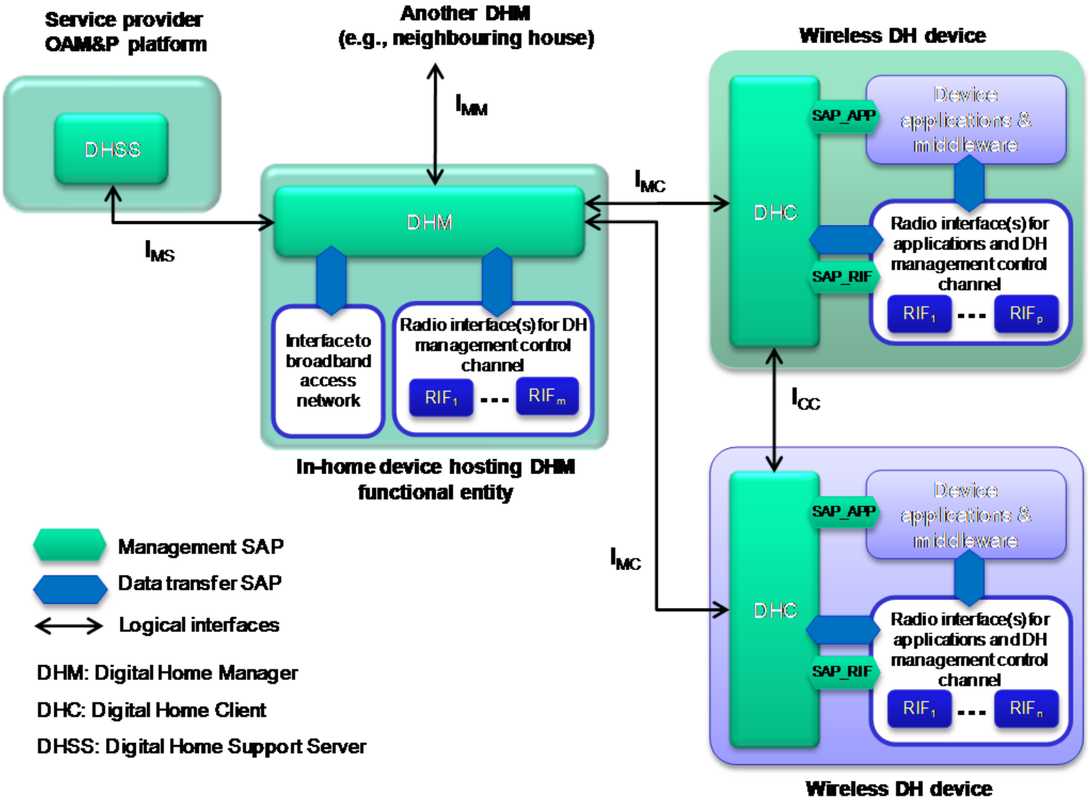

Figure 2. Functional architecture: functional entities and logical interfaces

Information exchange between functional entities requires the definition of four logical interfaces. Hence, as illustrated in Figure 2, interface I_{MC} is defined between DHM and DHCs, interface I_{CC} allows for direct signalling exchanges between DHCs, interface I_{MS} covers communication between DHM and DHSS and finally, interface I_{MM} enables the interaction between managers in neighbouring households. Details on the implementation of the different interfaces are given in Section 5.

Within a wireless DH device, the DHC functional entity is integrated within the DH device management functionalities and interacts with:

- Applications and middleware running in the device. In order to properly configure radio settings, DHC entity is aware of information such as application type (e.g., VoIP, Hi-Fi music streaming, video streaming, HDTV streaming, Internet access, etc.), required QoS (e.g., data rate) and involved end-point devices. This information is provided by applications, or by a specifically designed middleware, through a management service access point (SAP) denoted as SAP_APP in Figure 2.
- Radio InterFace(s) (RIF) and networking functions supported by the device. This interaction requires a management SAP denoted as SAP_RIF in Figure 2 which enables radio interface configuration and control as well as radio link monitoring.

Focusing now on the internals of the DHM entity, Figure 3 depicts the two core components embedded in this functional entity: a knowledge database and a decision making and learning logic. The knowledge database is generated as a result of the interactions with the managed DH devices (e.g., device profiles, radio link configurations and monitoring), the serving DHSS (e.g., spectrum availability, operational policies and profiles), potential neighbouring DHMs (e.g., inter-home interference coordination) and other possible relevant information sources such as local user management interfaces (e.g., graphical user interfaces to select high-level preferences by the final user), local spectrum sensors and in-home geo-location facilities. Models and related data needed to support decision making are also handled by the knowledge database. Part of this information is not to be static but it can be dynamically enhanced through learning processes. Decision-making and learning logic within the DHM entity is key to obtain an optimal performance of the coexisting wireless links from an interference point of view. This is achieved by smartly managing the radio transmission settings of the DHC-enabled devices. Furthermore, the decision-making logic needs to be designed to be robust against the presence of radio signals from other DH devices that might not operate under the control of a given DHM entity (e.g., DH devices from neighbouring households or legacy devices likely to coexist with DHC-enabled devices as a result of their gradual introduction in the DH). Decision-making and learning logic is realised through two main functions:

- Configuration of a new radio link. The DHM assists DHC-enabled devices in the configuration of their wireless interfaces. Configuration settings encompass, among others, wireless interface selection, operating spectrum band, channel bandwidth, central frequency or maximum transmission power. In the case of radio technologies relying on coexistence protocols to handle potential cross-interference (e.g., contention-based protocols), operational parameters of these protocols can also be adjusted to the specific home scenario. Radio link configuration decisions consider, among others, application requirements, propagation conditions between involved devices, spectrum availability, ongoing links, interference conditions and devices capabilities.
- Reconfiguration or termination of established radio links. Monitoring mechanisms for the established radio links (e.g., QoS monitoring) are used to assess whether the conditions that triggered a given configuration are still valid. Whenever a violation of the established QoS guarantees is detected, a reconfiguration of some ongoing links can be triggered. In order to minimise the impact of the reconfiguration process on the link quality, a maximum reconfiguration latency requirement can be established.

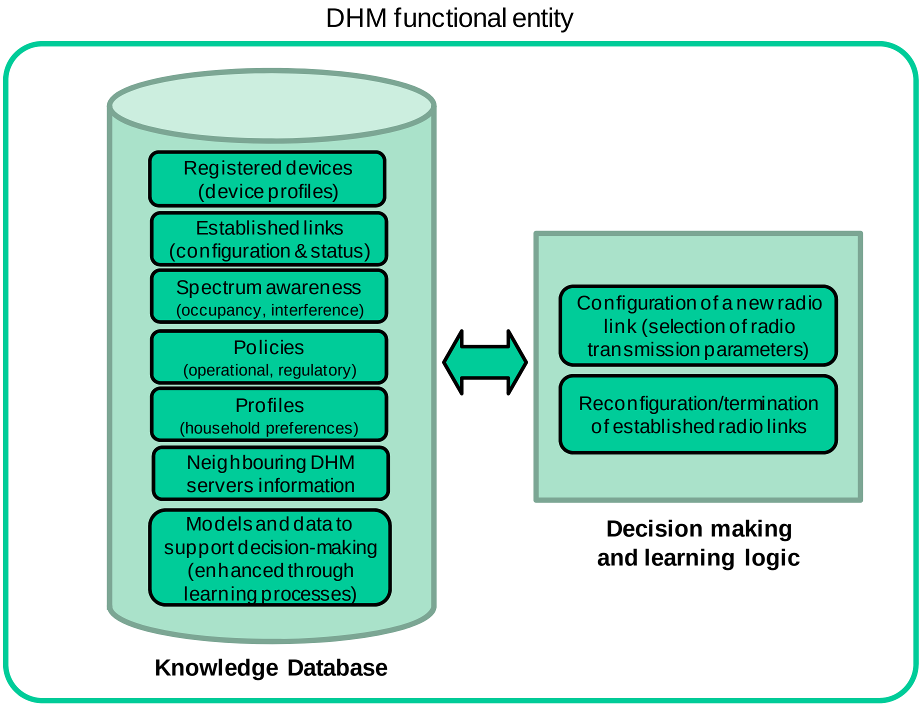

Figure 3. Main components of the Digital Home Manager (DHM) functional entity

The interaction between DHM and DHCs is built upon the set of procedures described in Table 1. Hence, a discovery procedure is needed for DH devices to detect the presence of a DHM hosting device and know about which DH management features and capabilities are offered. Once a DH device embedding a DHC entity is aware of the presence of a DHM in the household, a registration procedure is used to allow the DHM to be aware of the DH device and its characteristics and keep track of its operational status. On this basis, specific procedures for link configuration, modification and release are then used to manage in a coordinated way all potential coexisting radio links in the home environment. An information provisioning procedure is also defined for information exchange between the functional entities.

Table 1. Procedures between a DHM and the managed wireless DH devices

Procedure	**Description**
Discovery	Discovery procedure is used to detect the presence of DHM functionalities by DH devices.
Registration	When switched on, a DH device embedding a DHC entity shall register to a DHM that will serve as its master DHM. Capability exchange (e.g., supported radio interfaces) and initial operational settings (e.g., allocation of temporary device identifiers) are addressed through this procedure. Registration also encompasses security functions such as access control and initialisation of secure transfer mechanisms between devices.
Configuration	Procedure used to assist wireless DH devices in setting up their radio link configurations.
Modification	Used to enable a modification of a previously established link.
Release	Procedure used to let DHM know about a link deactivation by related devices or force its deactivation from DHM.
Information provisioning	The information provisioning procedure is used to exchange information between DH management functional entities (e.g., link status and measurements, performance monitoring).

Figure 4 shows an illustrative message chart for the establishment of a radio link between two potential DHC-enabled devices: a flat screen with several wireless connectivity options (Device A in Figure 4) and a network-attached storage (NAS) device capable of wirelessly streaming digital media content (Device B in Figure 4). Both devices are assumed to be registered in the DHM entity so that their presence and related capabilities are already stored in the DHM knowledge database. The description of the different steps shown in Figure 4 is as follows:

1) A user wishes to watch a movie in the flat screen (Device A). An interactive menu in the flat screen allows the user to select the media source from where the content is available.
2) The list of potential source devices, if not locally available or pre-configured in Device A, is to be provided to the flat screen device by the DHM functional entity. In this case, the information provisioning procedure will be used to retrieve available digital media server devices registered within the DHM along with their characteristics.
3) The user chooses the NAS device (Device B) as the source input.
4) At this point, Device A decides that a connection needs to be established between Device A and Device B and that radio link settings must be assisted by DHM.
5) Device A starts a link configuration procedure by sending the corresponding request to the DHM. The request message contains identifiers for the two devices to be interconnected and a description of the application characteristics that are expected to be supported (e.g., video streaming together with related control signalling).
6) In order to come up with a link configuration decision, DHM will check device capabilities, operational policies, spectrum awareness and other relevant data stored in the knowledge database. In case some required information is missing in the database, further interactions with the DH devices, neighbouring DHM and/or DHSS can be triggered, as illustrated in next steps.
7) As an example, the DHM could interrogate the DHSS about spectrum availability in license-exempt bands that can be opportunistically used (e.g., TV white spaces) or, in case of mobile operators serving as service providers, about possible use of mobile operator licensed bands (e.g., 2.6 GHz bands) when strict QoS guarantees are to be provided.
8) In order to have a more detailed characterisation of radio propagation between devices A and B, some sort of device-to-device monitoring or link testing mechanism can be triggered to accurately estimate propagation losses between devices and the levels of interference detected in different candidate channels. In this case, results of these tests will be sent back to the DHM. Link testing mechanisms can be established as a required feature to be supported by DHC-enabled devices.
9) Taking into account database information together with specifically collected data, the DHM functional entity can now decide on a suitable configuration to support the radio link between both devices.
10) Configuration settings are sent to Device A and Device B that can start the activation of the radio link.
11) Radio link establishment between devices takes place according to the specific radio technology procedures of the selected radio interfaces.
12) Once the radio link is successfully established, the DHM is notified and a monitoring phase is started where event-triggered or periodic transfer of radio link performance indicators will take place in order to trigger any needed modification.

The procedure described above is a general case intended to illustrate the different types of interactions between the DH devices and the DHM. Nevertheless, it’s worth noting that some steps might be omitted in particular instances. For example, step (2) used to retrieve the list of potential source devices and step (7) used to interrogate the DHSS can be both skipped if related information is already available and valid from previous interactions.

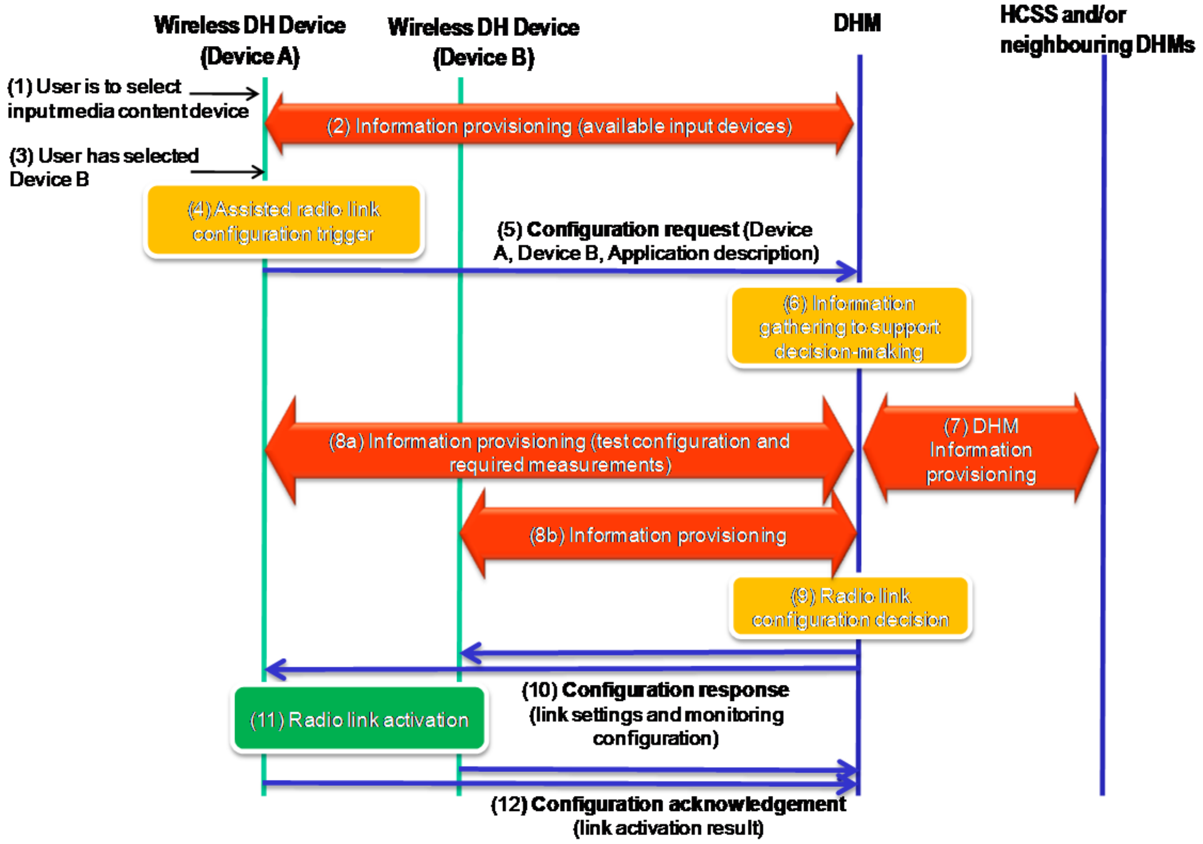

Figure 4. Message chart for the establishment of a DHM-assisted radio link

4. Use case analysis

In order to gain insight into the proposed solution framework a realistic indoor scenario has been considered. Measurements were taken in this scenario by placing a radio transmitter in two different locations. For each location, the received signal strength was recorded in different positions in rooms and corridors. Based on these measurements, the COST 231 indoor propagation model [14] was adjusted by minimizing the square error between collected real signal strength measurements and model predicted values. The formulated model was expressed as:

$$L(dB) = L_o + 20\log f\,(MHz) + 10\alpha \log d\,(m) + N_w L_w$$

where L_o=-27.55 dB, α is the propagation coefficient with the distance d(m), N_w is the number of traversed walls between transmitter and receiver and L_W is the attenuation of one wall dependant on the material and width. The considered indoor environment is a single floor of dimensions 16.8m x 30.4m organised in six different rooms as can be seen in the floor plan in Figure 5(a). Walls are made out of bricks with a width of 15 cm, while the ceiling height is around 3.5m. Based on the measurements, the estimated values of the propagation model in the considered scenario resulted to be α=2.6 and L_W=5.1 dB.

Let's consider in this indoor scenario the problem of establishing a DHM-assisted radio link between two DH devices described in previous section. The DH application is assumed to require 25 Mbit/s (turning into a capacity requirement of 100 Mbit/s at the physical layer after channel coding, radio frame adjustment, etc.). One of the DH devices is assumed to be located in one of the rooms as seen in Figure 5(a) and the other may be placed anywhere within the building.

Let's also consider that the spectrum awareness component in the knowledge database (which is implemented in the in-house device hosting the DHM functionality as illustrated in Figure 3) has identified 3 possible candidate spectrum pieces for this communication:

- Candidate #1: 20 MHz bandwidth in the 2.4 GHz ISM license-exempt band.
- Candidate #2: 16 MHz bandwidth in the 600 MHz TV White Space (TVWS) band that can be operated opportunistically.
- Candidate #3: 20 MHz bandwidth in a 2.6 GHz licensed band of the MNO serving as the DH management service provider.

The maximum allowed transmitted power is assumed to be 20 dBm in all three candidate bands.

Furthermore, a probabilistic spatial and temporal characterization of the different candidate spectrum pieces is retained in the knowledge database. In particular, for the spatial dimension, Figure 5 plots the Shannon-bound achievable bit rates in the scenario for the different candidate spectrum pieces. The area marked in black corresponds to the positions where the achievable bit rate is below the requirement of 100 Mb/s. For example, candidate #1 ensures that communication requirements can be met in 96.7% of the floor, as seen in Figure 5(a). However, being this a license-exempt band, it is possible that interferences arise from devices in neighboring buildings as well as from in-home legacy devices that do not operate under the control of the DHM. On this basis, Figure 5(b) shows the effect of an interference source of 20 dBm arisen from a neighboring building, located 13 m on the right side from the reference floor. In this case, the bit rate requirements would only be achieved in 37.9% of the floor.

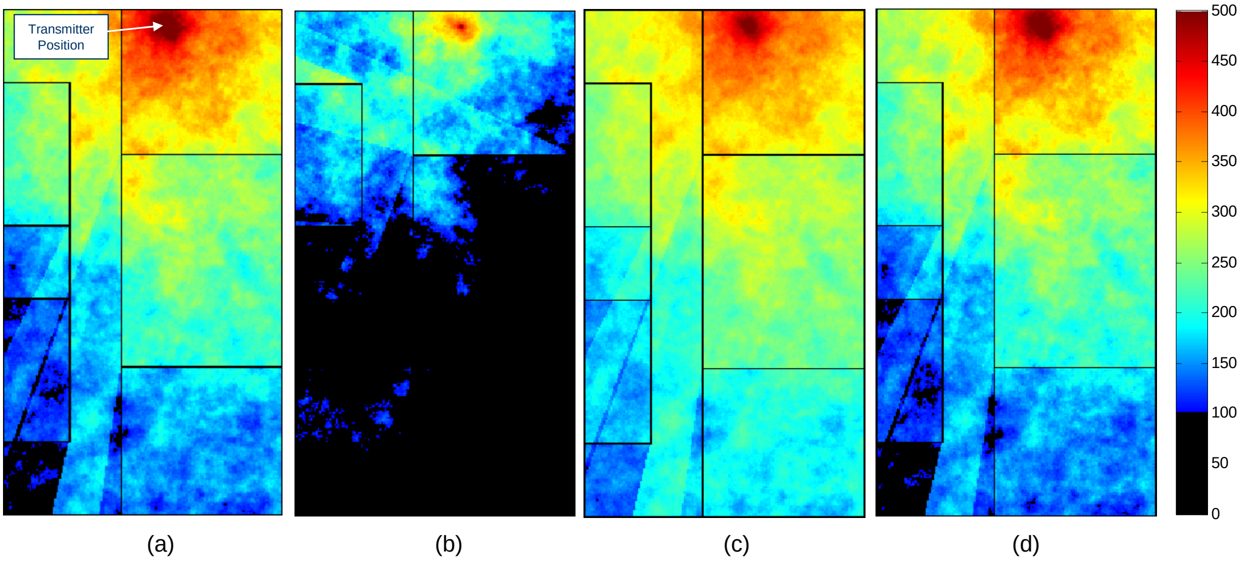

Figure 5. Achievable bit rates (Mbit/s) with the different configurations (a) Candidate #1, (b) Candidate#1 in the presence of an interference, (c) Candidate #2, (d) Candidate #3

Related to the temporal behavior of each candidate spectrum piece, let's assume the possible presence of external interferers that appear in different periods of time, so that it is possible to model the temporal behavior of a candidate spectrum piece as a 2 state Markov model: state L (Low) corresponds to the situation when no interference exists while state H (High) corresponds to the case when the interference exists. Thus, the knowledge database can just store the associated transition probabilities P_{HL} (i.e., probability of going from H to L in a time step unit Δt) and P_{LH}

(i.e., probability of going from L to H in a time step Δt). Note that all the transition probabilities can be obtained based on measurements of the behavior in the different spectrum pieces during system operation, and that the duration of the H and L states is given by $1/P_{HL}$ and $1/P_{LH}$ time step units, respectively.

For the example considered here, Table 2 summarizes the spectrum awareness information stored in the database for the identified candidate bands. It is assumed that the MNO band is always free of interference since it relies on the interference control mechanisms existing in the operator licensed band. In addition, the profile information within the knowledge database (see Figure 3) is assumed to retain some preferences with respect to the use of the three candidate bands in this particular building. In this example, ISM and TVWS bands are considered to have the same preference, while the MNO band has the lowest preference. In this way, the operator acting as DH service provider can have this band available for other services and only use it here whenever the other bands are not able to provide the bit rate requirements.

Table 2. Information stored in the knowledge database for the considered bands

Band	State measured at t=0	Fraction of area where bit rate requirements are met		State transition probabilities		Average Duration (Time steps)	
Candidate #1: ISM	L	$P_{A,L}$	96.7 %	P_{LH}	0.01	L ($1/P_{LH}$)	100
		$P_{A,H}$	37.9 %	P_{HL}	0.1	H ($1/P_{HL}$)	10
Candidate #2: TVWS	L	$P_{A,L}$	99.9%	P_{LH}	0.001	L ($1/P_{LH}$)	1000
		$P_{A,H}$	31.5%	P_{HL}	0.001	H ($1/P_{HL}$)	1000
Candidate #3: MNO	L	$P_{A,L}$	96.0%	P_{LH}	N/A	L	∞
		$P_{A,H}$	N/A	P_{HL}	N/A	H	0

In order to illustrate how the knowledge database can enhance the spectrum selection decision making, let's assume that the establishment of the considered DHM-assisted radio link starts at a given time t=T. The decision making needs to select a band based on the information stored in the database (i.e., the statistical characterisation shown in Table 2) plus the knowledge that in the last observation (at t=0 for reference) both the ISM and the TVWS bands were in the L state.

Under these circumstances, one possible simple criterion would be to select the ISM band because it remains a higher percentage of the time in L state. Alternatively, another criterion would be to choose the TVWS band on the presumption that it offers a longer duration of the L state. Figure 6 plots the probability of successful selection (i.e., the probability that the selected band is in the L state and that at the same time the bit rate requirements are met at the position of the receiver) as a function of time T elapsed since the last observation at t=0 for these two criteria (denoted as "Fixed Selection"). While for low T, the TVWS choice offers higher success probability because it is very likely that this band still remains in L state, when T increases it is eventually better to select the ISM band because of the higher probability for the L state. It can also be observed in Figure 6 that the performance of a random selection among the two bands falls in the middle between the two fixed selection criteria.

To overcome the trade-off in the selection of one or another band depending on the elapsed time T, we consider an advanced selection technique based on Partially Observable Markov Decision Processes (POMDP) [15] that exploits the transition probabilities stored in the table. Specifically, and based on the observation at t=0 and the state transition probabilities, the procedure computes in each time step Δt the probability that each band is in the H or in the L state (these are the so-called "belief probabilities" of states H and L, using POMDP terminology). To account for the spatial dimension, these probabilities are weighted by the fraction of area where the bit rate requirements can be met in each state. Then, at the time of selection T, the candidate band with the highest probability of being in state L and simultaneously meeting the bit rate requirements at the next time step is selected. Furthermore, to account for the preferences, this selection is only made between the ISM and TVWS bands, and only if the resulting highest probability among these two bands is below a given threshold (e.g., set to 0.5 in the provided results) the MNO band is chosen. Results in Figure 6 reflect that the advanced POMDP-based selection is able to provide the best performance among the considered schemes, by selecting always the channel that has the highest success probability.

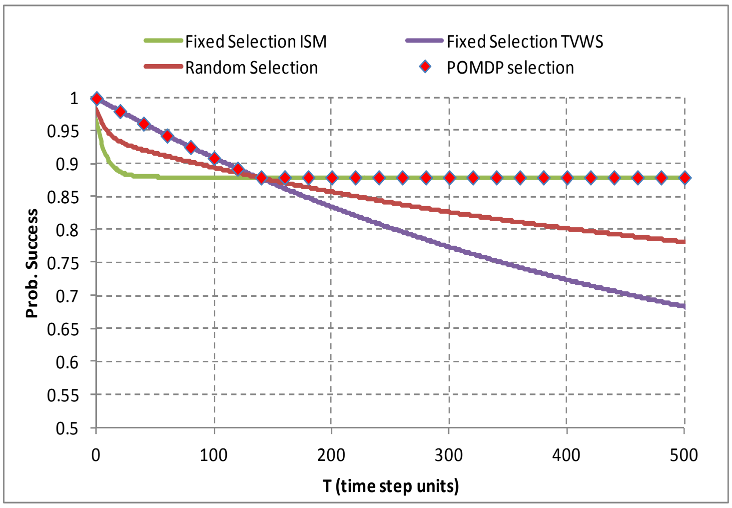

Figure 6. Success probability for different decision making schemes

5. Implementation aspects

The proposed solution to manage DH wireless communications can be implemented as an open solution addressing the specification of the four interfaces discussed in section 3 and illustrated in Figure 2. The implementation of the interfaces I_{MC} and I_{CC} between devices holding DHM and DHC functions requires (1) a protocol for the interaction between remote management entities, referred to as DH management protocol in the following, and (2) a transport mechanism to deliver such protocol messages between communicating devices where these entities are hosted.

As to the DH management protocol, a transport-agnostic implementation is preferred to facilitate the integration of the protocol with different underlying layers (e.g., DH management protocol signalling messages can be transferred by means of either layer 2 or layer 3 protocols). In addition, the development of the DH management protocol can capitalise on standards already conceived to facilitate networking in small business and consumer local networks such as ISO/IEC 29341 standards, commonly known as Universal Plug & Play (UPnP). The UPnP architecture [16] defines a way of controlling different types of devices (e.g., network-enabled consumer electronics equipment) built upon Extensible Markup Language (XML) and Simple Object Access Protocol (SOAP), which is the standard for Web messaging used in the Internet. Thus, implementation of DH management services could be built upon the elaboration of a new usage scenario within UPnP specifications in the same way as existing usage scenarios targeting, e.g., Audio/Video streaming, home automation and many others. The development of the specific DH management protocol messages and related procedures (from which a first high level view has been described in Section 3) can also benefit from ongoing activities in research projects where management protocols for the coordination of diverse devices engaged in so called *opportunistic networks* are addressed [7]. Standardisation efforts such as IEEE 802.19.1 [17] for TV white space coexistence can also be leveraged as well, as long as DH management system also embraces the possibility to coordinate the operation of in-home devices in TV bands (i.e. DHM will serve as the coexistence manager according to IEEE 802.19.1 framework).

As to the implementation of the transport mechanism for I_{MC} and I_{CC} interfaces to transfer DH management protocol messages, two main different approaches are anticipated. One approach consists in harmonizing the use of a common low cost radio technology supporting IP networking (e.g., Zigbee) that all DHC-enabled devices should incorporate. Hence, all DHC-enabled devices would be required to have installed one common, harmonised RIF for the establishment of a control network between them. This control network would provide delivery services to upper layer DH management protocols. Operation on bands with good propagation conditions within buildings (e.g., license-exempt 868 MHz band) and support of mesh networking capabilities might suffice to allow communication between any pair of wireless DH devices. Another different approach is the development of a transport mechanism enabling the transfer of control and management information between diverse devices that are not required to have a common harmonised RIF and instead rely on the exploitation of multi-hop and routing capabilities across diverse RIFs. In this context, a feasibility study on possible implementation options for control channels based on different radio protocols (e.g., Bluetooth, Wi-Fi, 3GPP Radio Resource Control, etc.) has recently been addressed in ETSI Technical Committee (TC) on Reconfigurable Radio Systems (RRS) [18], concluding that an implementation of the control channels based on a combination of different protocols is anticipated to be the most feasible.

As to the interaction of the DHM with the DHSS and other neighbouring DHMs, the implementation of interfaces I_{MS} and I_{MM} is expected to leverage the IP connectivity service provided by the broadband access network and benefit from widely accepted management protocols such as the CPE WAN Management Protocol (CWMP) specification from the Broadband Forum [19]. CWMP protocol is commonly used for the management of home gateway devices (e.g., DSL modems) and it has recently been approved by 3GPP as a protocol suitable for the management of femtocells. This protocol also uses SOAP web services to define a firewall friendly management protocol that allows for secure auto-configuration as well as other management functions within a common framework.

In terms of regulatory aspects, access to TV white spaces has been already regulated in US [20] and many other countries are expected to follow. The prevailing approach among regulators is so far a license-exempt regime based on geo-location and database access for spectrum authorisation. Also, regulations do not impose restrictions on the applications and technology used by devices exploiting this spectrum, other than limits on transmit power and out-of-band emission levels. Indeed, maximum permitted output power for personal/portable devices is set to 100 mW EIRP in the US, level that can suffice for most applications in the DH.

6. Concluding remarks

This paper has described a novel technical solution that enables business players to offer management services for DH wireless communications. The proposed solution is intended to improve the capacity and quality of DH wireless communications while relieving ordinary users from complex management tasks. The solution builds upon the introduction of management mechanisms in order to enhance the level of coordination of diverse wireless technologies in use within a DH environment and novel technologies that enable access to new spectrum resources for home communications. The functional architecture encompassing functional entities, interfaces, key components and related functions and main information procedures have been described. Over such a basis, a realistic indoor scenario use case has been discussed to gain insight into possible underlying principles behind spectrum selection decisions for establishing DH radio links. Finally, it has been argued that the implementation of the proposed DH management solution can actually leverage existing technologies as well as benefit from some ongoing standardisation and regulatory activities.

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