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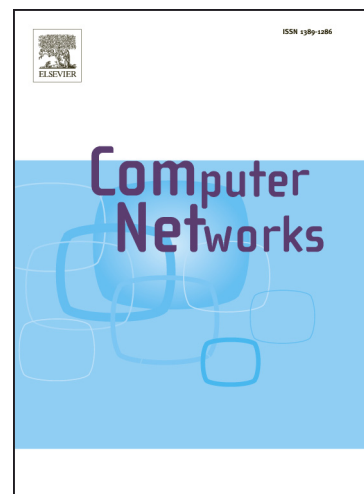
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A Cognitive Management Framework for Spectrum Selection

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Abstract—To increase cognitive radio (CR) operation efficiency, there has been an interest in enhancing the awareness level of spectrum utilization. In this context, this paper builds a new cognitive management functional architecture for spectrum selection (SS). It relies on a knowledge manager (KM) retaining a set of advanced statistics that track the suitability of spectral resources to support a set of heterogeneous applications under varying interference conditions. Based on this architecture, a novel proactive strategy is proposed for both SS and spectrum mobility (SM) functionalities. The required interactions between the proposed decision-making processes are described, and their capability to exhibit robustness to unexpected changes in the radio environment is highlighted. The results show that the proposed strategy efficiently exploits the KM support for low loads, while the SM functionality introduces significant gains for high loads with respect to other strategies. Finally, to assess the practicality of the proposed approach, the signaling requirements in the radio interface are evaluated.

I. CONTEXT/MOTIVATION

The cognitive radio (CR) paradigm has led to the emergence of intelligent radios that automatically adjust their behavior based on active monitoring of the environment [1, 2]. In this context, the introduction of cognitive techniques for the management of wireless networks will lead to enhanced robustness by capitalizing on the learning capabilities intrinsic to cognitive systems. Strengthening these cognitive techniques is of great interest for optimizing cognitive management functions.

The flexibility provided by CR is of paramount importance to enable the so-called dynamic spectrum access (DSA), a new communication paradigm that proposes the use and sharing of available spectrum in an opportunistic manner to increase its usage efficiency. In this context, there has been a recent trend towards improving the awareness level of CR systems. Specifically, there has been an interest in recording, storing, and accessing new relevant information about the radio environment. This information may take the form of, for instance, a long-term characterization acquired offline and retained in a database to guide CR operation [3, 4].

Extending these previous works, the main objective of this paper is to propose a framework for exploiting advanced cognitive management functionalities to improve CR operation efficiency. In particular, the proposed framework would make it possible to manage the most relevant knowledge characterizing the radio environment and to assist in the spectrum management decision-making process accordingly.

The potential benefits of exploiting cognitive management support have been established in many studies [5–7]. In this respect, many recent proposals have attempted to develop new models and efficient architectures for building new cognitive management systems in emerging environments. For instance, the authors in [8] proposed to introduce cognitive management into the Future Internet (FI) to address the inherently increased complexity. In [9], a cognitive management architecture was suggested to offer an autonomous optimization of resource usage and performance in home wireless environments. In [10], a novel strategy to exploit cognitive features for supporting ultra-wideband (UWB) technology was proposed. The proven usefulness of cognitive capabilities has stimulated the initiation of many research projects (e.g. [11–13]) and standardization activities (e.g. [14, 15]) to further strengthen and promote the use of cognitive management systems.

In particular, there has been increasing interest in relying on cognitive management tools to assist in spectrum selection (SS). In this regard, some proposals have focused on overcoming the uncertainty of the radio environment by exploiting different forms of cognition. In particular, much care has been paid to reinforcement learning [16–20], partially observable Markov decision processes [21, 22], and fuzzy logic [23] tools known to cope well with uncertainty. Other proposals have attempted to acquire a useful stationary awareness level to assist in SS. For instance, the authors in [24, 25] proposed to combine sensing with short- and long-term information about primary users to determine the most likely unoccupied channels. In [26], multi-time-scale predictive primary statistical models were built based on sensing reports to maximize spectrum utilization. In [27], a set of topology-aware distributed algorithms was proposed to enable self-coordination of spectra among different access networks.

Although these proposals have been shown to efficiently assist in SS in different scenarios, they all rely on some form of cognitive support that is jointly developed with the specific SS decision-making process. This common feature has strongly constrained the introduction of cognitive support by forcing it to be specific to each application, which reduces the scope of its applicability. To overcome this limitation, there has been increasing interest in developing advanced cognitive management functionalities independent of the decision-making process. The interest in this topic has been reflected in most of the recently proposed models and architectures for emerging environments, such as the functional architecture proposed in [28] by the European Telecommunications

Standardization Institute (ETSI) for Reconfigurable Radio Systems (RRSs) and its subsequent extension for opportunistic networks (ONs) [29].

Drawing inspiration from these architectures, this paper proposes a new generic cognitive management functional architecture for assisting the spectrum management decision-making process. The proposed architecture integrates the fittingness factor concept proposed in [4] to track the suitability of spectral resources to support a set of heterogeneous applications subject to unknown changes in interference conditions. Using the architecture proposed in [30] as a building block, these suitability levels are managed within a standalone knowledge management domain external to the decision-making domain. Due to this separation, generic advanced cognitive functionalities can be developed within the knowledge management domain independently from the decision-making process. Then, these functionalities can be properly instantiated in different scenarios to provide the most relevant support to each task performed by the decision-making process.

From this perspective, the main novel aspects of this paper are two-fold. The first main contribution is the development of a cognitive management functional architecture for assisting the spectrum management decision-making process based on the fittingness factor concept. The proposed architecture relies on a knowledge management domain managing a set of advanced statistics about observed fittingness factor values to efficiently monitor the suitability of spectrum resources subject to unknown changes in interference conditions. The second contribution is the development of a novel proactive spectrum management strategy exploiting the estimated suitability of spectrum resources for assisting both SS and spectrum mobility (SM) functionalities while being robust to unexpected changes in interference levels at any traffic load of supported applications. The interactions among the relevant functional blocks for the associated procedures are described through message sequence charts (MSCs).

The remainder of this paper is organized as follows. A cognitive management functional architecture for assisting the spectrum management decision-making process is constructed in Section II. The proposed architecture is instantiated to integrate the fittingness factor concept to monitor the time-varying suitability of spectrum resources in Section III. Based on estimated fittingness factors, a new proactive strategy that jointly assists SS and SM functionalities is proposed in Section IV, and the associated procedures are described through MSCs. An acquisition strategy performing the required configurations following these procedures is proposed in Section V. The results are presented in Section VI, including an evaluation of the performance in terms of dissatisfaction probability and an assessment of the introduced signaling requirements at the radio interface. The conclusions and future directions are provided in Section VII.

II. FUNCTIONAL ARCHITECTURE

The problem considered here is the selection of the spectrum to be assigned to a set of L radio links that need to be established between pairs of terminals and/or network infrastructure

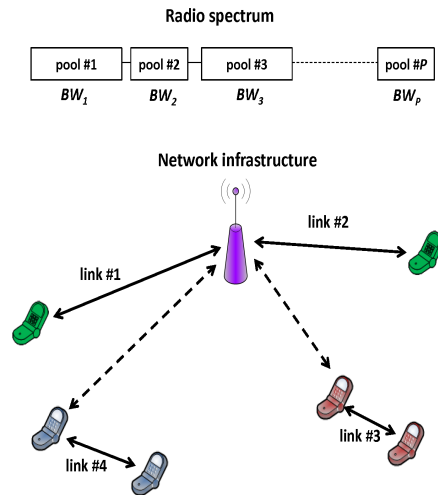


Fig. 1. Example of established radio links

nodes. The purpose of the l -th radio link is to support the communication flow generated by a given application (e.g., voice, web browsing, or video call) whose requirements are expressed in terms of a required bit rate $R_{req,l}$ and duration $T_{req,l}$. As shown in the example of Fig. 1, the established radio links may connect a terminal node to a network infrastructure (links #1 and #2) or two terminal nodes (links #3 and #4). To meet the heterogeneous requirements from diverse applications, it is assumed that the network infrastructure is responsible for assigning suitable spectrum resources to each radio link. In this respect, the spectrum is modeled as a set of P blocks (denoted as “pools” in this paper), each of bandwidth BW_p . The SS decisions made on the network infrastructure side are indicated to mobile terminals through suitable control channels (denoted in Fig. 1 as dashed lines in case there is no data connection with the network infrastructure).

Based on the above considerations, the functional architecture depicted in Fig. 2 is proposed. Inspired by the ETSI-RRS architecture [28, 29], two cognitive management entities are introduced on both the terminal and network infrastructure sides to manage relevant knowledge about the environment. In this architecture, most of the cognitive management functionalities are executed on the network infrastructure side with support from the terminal side. Specifically, as illustrated in Fig. 2, the execution involves the following entities:

- 1) The knowledge management entity, which is responsible for storing and managing the relevant knowledge obtained from the radio environment for use in making decisions by the decision-making entity. It is composed of a knowledge manager (KM) that monitors the suitability of existing spectral resources to support a set of heterogeneous applications. The KM monitoring is based on information retrieved from a knowledge database (KD) that stores a set of relevant statistics about the environment. The KD also retains the list of available spectrum pools obtained from a spectrum

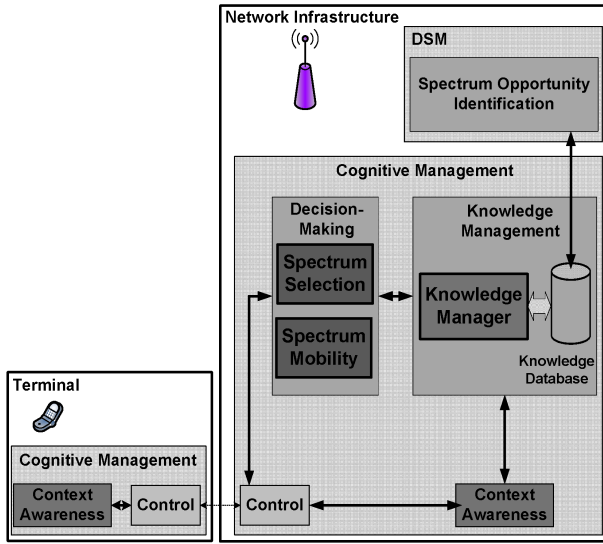


Fig. 2. Functional architecture of the proposed cognitive management framework for SS

opportunity identification functionality residing in an external dynamic spectrum management (DSM) domain. The interested reader is referred to [28] for details about DSM.

- 2) The decision-making entity, which is responsible for assigning the appropriate pools to different links. For that purpose, it interacts with the KM that will provide the relevant information for the decisions to be made. Decision making is split into two functional entities: the SS functionality, which will pick up a suitable pool for each communication whenever a new request for establishing a radio link arrives, and the SM functionality, which will perform the reconfiguration of assigned pools whenever changes occur in the environment and better pools can be found for some links.
- 3) The context awareness entity, which is responsible for taking measurements on both the terminal and network infrastructure sides. Actual measurements of the performance achieved in a given link when using a certain spectrum pool are exploited by the KM, which will retain these observations for supporting future SS decisions.

Finally, the control modules depicted in Fig. 2 illustrate the need for control message exchange between the terminal and network infrastructure to support the diverse cognitive management mechanisms and procedures (e.g., the establishment/release of radio links and measurement reporting). The interested reader is referred to [31, 32] for details on possible implementation options of this exchange of control messages through the use of a cognitive control channel.

It is worth mentioning that the considered centralized setting mainly targets local environments (e.g., Digital Home) where access to a central point can be relatively easy. Nevertheless, the proposed framework also accepts decentralized or hybrid (e.g., centralized database for TV whitespace and decentralized for ISM band) architectures. In such scenarios, decision

making functionalities (i.e., SS and SM) would be executed at each terminal based the support provided by a local knowledge management domain. More details about how to build such local knowledge domains are given at the end of Section III.

III. KNOWLEDGE MANAGEMENT

In this section, the proposed functional architecture is implemented to monitor the time-varying suitability of spectrum resources to support a set of heterogeneous applications. To this end, the fittingness factor concept is introduced, and the relevant functional blocks of the proposed architecture are described for the considered centralized setting. Some initial guidelines about the applicability to decentralized scenarios are provided at the end of the section.

A. Fittingness factor definition

To assess the suitability of spectral resources to meet the requirements of different applications, the so-called fittingness factor ($F_{l,p}$) was introduced in [4] as a metric capturing how suitable each p -th spectrum pool is for the application supported by the l -th radio link. $F_{l,p}$ assesses the suitability in terms of the bit rate that can be achieved while operating in the spectrum pool p (denoted as $R(l,p)$) versus the bit rate required by the corresponding application ($R_{req,l}$).

From a general perspective, the fittingness factor can be formulated as a function of the utility $U_{l,p}$ that the l -th link can obtain from the p -th pool, where the utility is defined as [33]:

$$U_{l,p} = \frac{\left(\frac{R(l,p)}{R_{req,l}}\right)^\xi}{1 + \left(\frac{R(l,p)}{R_{req,l}}\right)^\xi} \quad (1)$$

where ξ is a shaping parameter that allows the function to capture different degrees of elasticity with respect to the required bit rate. The achievable bit rate by link l using pool p ($R(l,p)$) will depend on the radio and interference conditions present in pool p .

Based on the above concept, it is proposed to use the fittingness factor function previously proposed in [4]:

$$F_{l,p} = \frac{1 - e^{-\frac{K \times U_{l,p}}{\frac{R(l,p)}{R_{req,l}}}}}{\lambda} \quad (2)$$

where K is a shaping parameter and λ is a factor that normalizes the maximum of the fittingness factor to one that is given by:

$$\lambda = 1 - e^{-\frac{K}{(\xi-1)^{\frac{1}{\xi}} + (\xi-1)^{\frac{1-\xi}{\xi}}}} \quad (3)$$

To illustrate the behavior of the proposed fittingness factor function, Fig. 3 plots both $F_{l,p}$ and $U_{l,p}$ functions for $\xi=5$ and $K=1$. While $U_{l,p}$ monotonically increases with the bit rate $R(l,p)$, $F_{l,p}$ increases up to the maximum at $R(l,p) = \sqrt[\xi]{\xi-1} \cdot R_{req,l}$, and then decreases. This behavior reduces the value of the fittingness factor whenever the available bit rate is much higher than the required one, thus resulting in a more efficient usage of spectral resources than just considering the pure utility $U_{l,p}$.

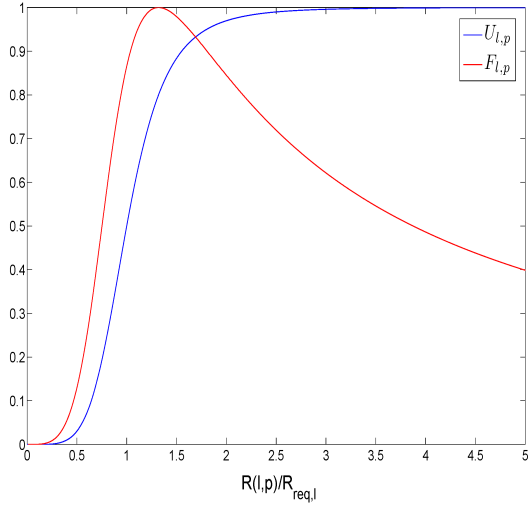


Fig. 3. Fittingness factor and utility functions with $\xi=5$ and $K=1$.

B. Knowledge database

To enable a global characterization of the suitability of a given pool p to a given link l based on the history of using this pool, the information retained in the KD will be associated to some statistics of $F_{l,p}$. The database will be fed by measurements extracted from the radio environment. In particular, the measurement of $R(l,p)$ of active link/pool pairs will be obtained, from which the current value of $F_{l,p}$ will be computed following (2) and stored in the database together with a timer $\Delta k_{l,p}$ indicating the time elapsed since the measurement was obtained.

Considering that $F_{l,p}$ values can be associated with two states, LOW ($<\delta_{l,p}$) or HIGH ($\geq\delta_{l,p}$), and assuming a stationary behavior of the different pools during the system operation, the following statistics are also generated and stored in the database based on the previously obtained measurements of $R(l,p)$ and $F_{l,p}$:

- The probability $P_L^{l,p}(\delta_{l,p})$ of observing a LOW fittingness factor:

$$P_L^{l,p}(\delta_{l,p}) = \text{Prob}[F_{l,p} < \delta_{l,p}] \quad (4)$$

- The probability $P_H^{l,p}(\delta_{l,p})$ of observing a HIGH fittingness factor:

$$P_H^{l,p}(\delta_{l,p}) = 1 - P_L^{l,p}(\delta_{l,p}) \quad (5)$$

- The average of observed LOW fittingness factor values:

$$\overline{F_L^{l,p}} = E(F_{l,p} | F_{l,p} < \delta_{l,p}) \quad (6)$$

where $E(X)$ denotes the expected value of random variable X .

- The average of observed HIGH fittingness factor values:

$$\overline{F_H^{l,p}} = E(F_{l,p} | F_{l,p} \geq \delta_{l,p}) \quad (7)$$

Furthermore, to monitor fittingness factor variability, the following statistical metrics are considered to determine the extent to which the state of the fittingness factor is likely to remain constant for a certain time n :

- Given $F_{l,p}$ is LOW at a given time instant k , the probability that $F_{l,p}$ will be LOW at each time instant up to time $k+n$; $n \in \mathbb{N}$ defined as follows:

$$P_{L,L}^{l,p}(n, \delta_{l,p}) = \text{Prob}[F_{l,p}(k+j) < \delta_{l,p}, \forall j \in \{1, \dots, n\} | F_{l,p}(k) < \delta_{l,p}] \quad (8)$$

where $F_{l,p}(k)$ denotes the observed $F_{l,p}$ value at time k .

- Given $F_{l,p}$ is HIGH at a given time instant k , the probability that $F_{l,p}$ will be HIGH at each time instant up to time $k+n$; $n \in \mathbb{N}$ defined as follows:

$$P_{H,H}^{l,p}(n, \delta_{l,p}) = \text{Prob}[F_{l,p}(k+j) \geq \delta_{l,p}, \forall j \in \{1, \dots, n\} | F_{l,p}(k) \geq \delta_{l,p}] \quad (9)$$

C. Knowledge manager

The KM plays a key role between the knowledge management and decision-making domains of the proposed architecture. It manages the information retained in the KD to determine which information about the environment is most relevant to the decision-making entity.

The KM keeps an estimation of $F_{l,p}$ values based on the statistics available at the KD. These estimated values, denoted as $\hat{F}_{l,p}$, are obtained following Algorithm 1 and are provided upon request to the decision-making module. The estimate $\hat{F}_{l,p}$ is determined based on whether the state of the $F_{l,p}$, stored in the KD $\Delta k_{l,p}$ time units before, is likely to be still valid at the KM execution time (this criterion is checked on lines 5 and 11 of Algorithm 1 with respect to the significance thresholds Thr_LOW and Thr_HIGH , respectively). In such case, $\hat{F}_{l,p}$ is set to the last measured $F_{l,p}$ value (lines 6 and 12). Otherwise, $\hat{F}_{l,p}$ is randomly set to either $\overline{F_L^{l,p}}$ or $\overline{F_H^{l,p}}$, i.e., the average $F_{l,p}$ values in the LOW and HIGH states, respectively, with probabilities $P_L^{l,p}(\delta_{l,p})$ and $1 - P_L^{l,p}(\delta_{l,p})$ (lines 8 and 14). Once all link/pool pairs have been explored, the list of all estimated fittingness factor values ($\{\hat{F}_{l,p}\}_{1 \leq l \leq L, 1 \leq p \leq P}$) is returned back to the decision-making entity (line 19).

The KM also captures relevant changes in these estimated values and informs the decision-making module for its consideration. In this respect, the KM keeps a change flag (denoted as *Change_detected*) that is set if the estimate $\hat{F}_{l,p}$ goes from LOW to HIGH or vice versa.

The knowledge management domain may also be applied to decentralized architectures. For such scenarios, a local KD can be constructed at each of the terminals. The local KD would retain $F_{l,p}$ values and the list of statistics defined in Section III-B obtained based on local observations made by each terminal. For small neighborhoods with homogeneous interference conditions, each terminal may cooperate with its neighbors via context awareness modules to get the most recent $F_{l,p}$ value observed in the neighborhood together with the timer $\Delta k_{l,p}$. Then, the KM can be executed at each of these terminals to determine a local $\hat{F}_{l,p}$ estimate based on the local KD statistics.

Algorithm 1 Knowledge Manager

```

indent=1em
1: Knowledge Manager
2: for  $l=1$   $L$  do
3:   for  $p=1$   $P$  do
4:     if  $F_{l,p}$  is LOW then
5:       if  $P_{L,L}^{l,p}(\Delta k_{l,p}, \delta_{l,p}) \geq Thr\_LOW$  then
6:          $\hat{F}_{l,p} \leftarrow F_{l,p}$ ;
7:       else
8:         Estimate  $F_{l,p}$  as follows:


$$\hat{F}_{l,p} = \begin{cases} \overline{F_{L,p}^{l,p}} & \text{with probability } P_{L,p}^{l,p}(\delta_{l,p}), \\ \overline{F_{H,p}^{l,p}} & \text{with probability } 1 - P_{L,p}^{l,p}(\delta_{l,p}). \end{cases}$$


9:       end if
10:      else
11:        if  $P_{H,H}^{l,p}(\Delta k_{l,p}, \delta_{l,p}) \geq Thr\_HIGH$  then
12:           $\hat{F}_{l,p} \leftarrow F_{l,p}$ ;
13:        else
14:          Estimate  $F_{l,p}$  as follows:


$$\hat{F}_{l,p} = \begin{cases} \overline{F_{L,p}^{l,p}} & \text{with probability } P_{L,p}^{l,p}(\delta_{l,p}), \\ \overline{F_{H,p}^{l,p}} & \text{with probability } 1 - P_{L,p}^{l,p}(\delta_{l,p}). \end{cases}$$


15:        end if
16:      end if
17:    end for
18:  end for
19: return  $(\{\hat{F}_{l,p}\}_{1 \leq l \leq L, 1 \leq p \leq P})$ 
    
```

IV. SPECTRUM MANAGEMENT DECISION MAKING

The proposed fittingness factor function should have applicability to the SS decision-making process. The aim of this process is to allocate, for a given link l , the best spectrum pool $p^*(l)$ among the list of available pools (Av_Pools), i.e., those that are not currently assigned to any other link. To maximize the likelihood of observing a HIGH $F_{l,p}$ value up to the end of the link session duration $T_{req,l}$, a proactive criterion is proposed:

$$p^*(l) = \arg \max_{p \in Av_Pools} (g(\hat{F}_{l,p})) \quad (10)$$

where:

$$g(\hat{F}_{l,p}) = \begin{cases} P_{H,H}^{l,p}(\Delta k_{l,p} + T_{req,l}, \delta_{l,p}) & \text{if } \hat{F}_{l,p} \text{ is HIGH} \\ 0 & \text{if } \hat{F}_{l,p} \text{ is LOW} \end{cases} \quad (11)$$

In the very specific case of multiple pools fulfilling the maximization, the pool with the highest $\hat{F}_{l,p}$ value is selected.

Note that no knowledge about the actual radio conditions experienced in the different pools is required at link establishment because the selection decision is based solely on an estimation of $F_{l,p}$ values ($\hat{F}_{l,p}$).

Based on the proposed proactive criterion, both the SS and SM functionalities of the decision-making process are described in the following, together with the associated procedures.

A. Spectrum selection

The SS functionality will be executed every time the start of a new application requires the establishment of a radio link to support communication. Fig. 4 presents the MSC associated

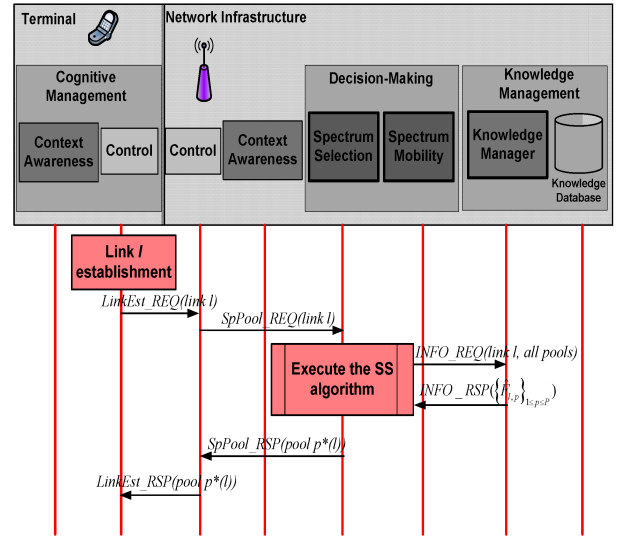


Fig. 4. MSC for SS at the establishment of radio link l

with the execution of this functionality at the establishment of link l . The control module on the terminal side sends a link establishment request ($LinkEst_REQ(link\ l)$) to its counterpart on the network infrastructure side. The latter asks the SS entity to provide a suitable pool for that link ($SpPool_REQ(link\ l)$). Then, the fittingness factor-based SS algorithm described in Algorithm 2 and based on equations (10)(11) is executed. If the set of available pools (Av_Pools) is empty, the request is rejected (line 3). Otherwise, the SS entity asks the KM for the estimation $\{\hat{F}_{l,p}\}_{1 \leq p \leq P}$ of all pools by sending the $INFO_REQ(link\ l, all\ pools)$ message in Fig. 4. The response is carried in the $INFO_RSP(\{\hat{F}_{l,p}\}_{1 \leq p \leq P})$ message. Based on the provided $\hat{F}_{l,p}$ values, the proactive criterion of (10) is used to select the pool $p^*(l)$ that is most likely to provide a HIGH $F_{l,p}$ value up to the end of the link session (line 7 of Algorithm 2). The SS process is completed when the selected pool is communicated to the control module on the network infrastructure side ($SpPool_RSP(pool\ p^*(l))$) and then forwarded to its counterpart on the terminal side ($LinkEst_RSP(pool\ p^*(l))$).

Algorithm 2 Fittingness factor-based SS

```

indent=1em
1: if link  $l$  establishment request then
2:   if  $Av\_Pools = \emptyset$  then
3:     Reject request;
4:   else
5:     Send  $INFO\_REQ(link\ l, all\ pools)$  to the KM;
6:     Get  $INFO\_RSP(\{\hat{F}_{l,p}\}_{1 \leq p \leq P})$  from the KM;
7:      $p^*(l) \leftarrow \arg \max_{p \in Av\_Pools} (g(\hat{F}_{l,p}))$ ;
8:   end if
9: end if
    
```

B. Spectrum mobility

The SM functionality attempts to ensure highly efficient allocation of the available spectrum pools to each of the established radio links. Therefore, whenever an event that might

have influence on the SS decision-making process occurs, the SM will be executed. Such events include (1) a spectrum pool being released due to finalization of the corresponding application, or (2) a change in the suitability of the available spectrum pools being detected.

Algorithm 3 Fittingness factor-based SM

```

indent=1em
1: if (link  $l^*$  release) ( $Change\_detected=true$  then
2:   Send  $INFO\_REQ(all\ links,\ all\ pools)$  to the KM;
3:   Get  $INFO\_RSP(\{\hat{F}_{l,p}\}_{1 \leq l \leq L, 1 \leq p \leq P})$  from the KM;
4:    $new\_Assigned \leftarrow \emptyset$ ;
5:   Sort  $Active\_Links$  in decreasing order of  $R_{req,l}$ ;
6:   for  $l=1$  | $Active\_Links$ | do
7:      $new\_p^*(l) \leftarrow \arg \max_{p \in Av\_Pools} g(\hat{F}_{l,p})$ ;
8:     if (( $\hat{F}_{l,p^*(l)}$  is LOW) ( $\hat{F}_{l,new\_p^*(l)}$  is HIGH))
9:       ( $p^*(l) \in new\_Assigned$ ) then
10:       $p^*(l) \leftarrow new\_p^*(l)$ ;
11:       $new\_Assigned \leftarrow new\_Assigned \cup \{new\_p^*(l)\}$ ;
12:     else
13:       $new\_Assigned \leftarrow new\_Assigned \cup \{p^*(l)\}$ ;
14:     end if
15:   end for
16:    $Assigned \leftarrow new\_Assigned$ ;
17: end if
    
```

As detailed by Algorithm 3, the proposed fittingness factor-based SM algorithm first gets the current $\{\hat{F}_{l,p}\}_{1 \leq l \leq L, 1 \leq p \leq P}$ estimates from the KM. Then, it explores the list of currently active links ($Active_Links$) in decreasing order of the required throughputs ($R_{req,l}$) to prioritize the neediest links. The reconfiguration decision for each active link is based on a comparison between the in use pool ($p^*(l)$) and the currently best pool in terms of $g(\hat{F}_{l,p})$ ($new_p^*(l)$) (line 8). Specifically, if $\hat{F}_{l,p^*(l)}$ is LOW and $\hat{F}_{l,new_p^*(l)}$ is HIGH, a Spectrum handover (SpHO) from $p^*(l)$ to $new_p^*(l)$ is performed because $new_p^*(l)$ fits better link l . Finally, as reflected in the condition of line 9, the same SpHO should be performed if $p^*(l)$ is no longer available to link l after being reassigned to another active link in the previous iterations of the loop of line 6. Once all active links are explored, the list of assigned pools is updated to consider all SpHOs that need to be performed as a result of the algorithm (line 16).

As an example, Fig. 5 describes the process involving SM due to radio link release. Upon the release of a given link l , the control module on the terminal side informs its counterpart on the network infrastructure side ($LinkRelease_REQ(link\ l)$). In turn, the control module at the network infrastructure asks the SS entity to release the corresponding pool ($SpPool_REL(link\ l,\ pool\ p^*(l))$) and informs its counterpart on the terminal side once complete ($LinkRelease_RSP(link\ l)$). If there is at least one active link l' with a LOW $\hat{F}_{l',p^*(l')}$ value, the SS entity asks the SM entity to perform a spectrum reconfiguration ($Trigger$). To achieve that, the SM entity consults the KM to obtain the relevant information about all links/pools ($INFO_REQ(all\ links,\ all\ pools)$). The KM provides the SM entity with the current estimation of fittingness factor values ($INFO_RSP(\{\hat{F}_{l,p}\}_{1 \leq l \leq L, 1 \leq p \leq P})$). Based on this information, the SM algorithm is executed and the links/pools to be reconfigured are indicated to the control module on the network infrastructure side ($SpPool_Reconfig(link\ l^*,\ pool\ p^*)$). For

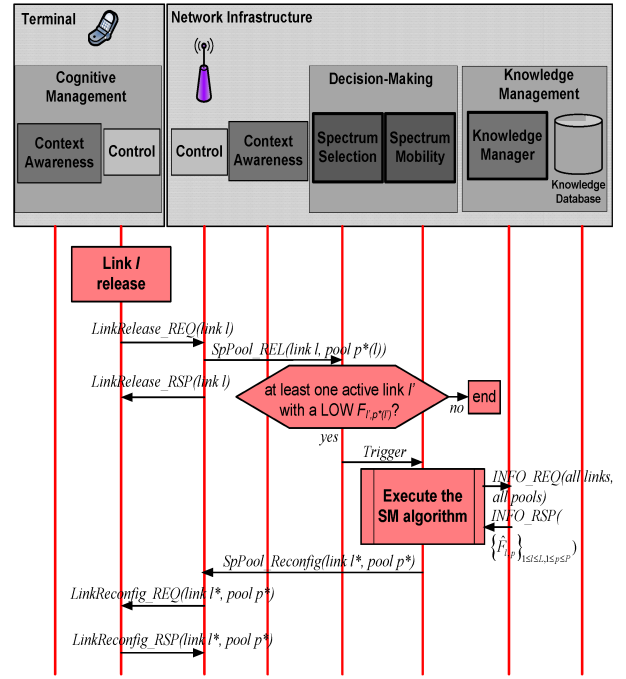


Fig. 5. MSC for SM due to the release of radio link l

each of these link/pool pairs, the control module on the terminal side is asked to execute the reconfiguration decision ($LinkReconfig_REQ(link\ l^*,\ pool\ p^*)$). Once this decision is made, an acknowledgment is sent back to the counterpart on the network infrastructure side ($LinkReconfig_RSP(link\ l^*,\ pool\ p^*)$).

V. CONTEXT AWARENESS

The context awareness functional entity is of major importance to enable the network infrastructure domain to assess the actual conditions experienced by the different applications over the established radio links. This assessment ability enables the cognitive cycle to be closed and the decision-making processes on the network infrastructure side (e.g., SM) to react to any change, thus allowing for a highly efficient allocation of radio resources.

In particular, at link establishment, the network infrastructure side decides an acquisition strategy depending on the dynamics of the radio environment. In general, two different acquisition strategies can be considered, a periodic strategy in which context awareness modules periodically report measurements to the KD or an event-triggered strategy in which measurements reports are generated only when some relevant conditions are met. If the radio environment changes frequently, a simple periodic acquisition strategy can be used. Conversely, in less varying environments, an event-based acquisition strategy is preferred to avoid unnecessary signaling loads between context awareness modules. In this paper, we propose the use of the event-triggered acquisition strategy described by Algorithm 4. Measurement reports in this case are generated only if the currently measured $F_{l,p}$ value ($current_F_{l,p}$) is LOW and the last reported $F_{l,p}$ value ($rep_F_{l,p}$) was HIGH or vice versa. As it will be shown later in

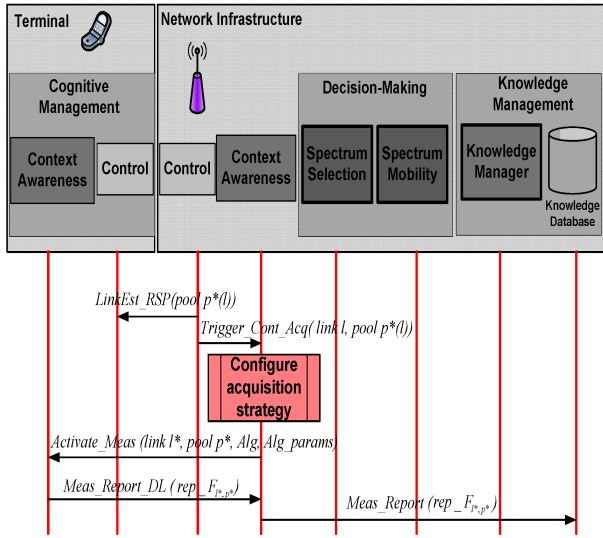


Fig. 6. MSC for the configuration of measurements

the results section, this strategy can provide better performance than a periodic acquisition strategy.

As shown in Fig. 6, following a link establishment, the control module on the network infrastructure side asks its associated context awareness module to trigger a context acquisition strategy ($Trigger_Cont_Acq(link\ l, pool\ p^*(l))$). The latter configures the acquisition strategy and asks its counterpart on the terminal side to activate a set of measurements according to the configured strategy ($Activate_Meas(link\ l^*, pool\ p^*, Alg, Alg_params)$), where Alg and Alg_params denote the considered acquisition strategy algorithm and its optional set of parameters, respectively. These measurements are later reported by the context awareness module on the terminal side ($Meas_Report_DL(rep_F_{l^*,p^*})$) and then combined with the measurements performed on the network infrastructure side before being sent to the KD ($Meas_Report(rep_F_{l^*,p^*})$).

Algorithm 4 Event-Triggered acquisition strategy

```

indent=1em
1: for  $p=1$   $P$  do
2:   Compute  $current\_F_{l,p}$  according to (2);
3:   if (( $current\_F_{l,p}$  is LOW) ( $rep\_F_{l,p}$  is HIGH))
4:     (( $current\_F_{l,p}$  is HIGH) ( $rep\_F_{l,p}$  is LOW)) then
5:      $rep\_F_{l,p} \leftarrow current\_F_{l,p}$ ;
6:     Generate  $Meas\_Report(rep\_F_{l,p})$ ;
7:   end if
8: end for

```

VI. SIMULATION RESULTS

A. Simulation Model

To evaluate the effectiveness of the proposed framework in assisting in the spectrum management decision-making process, $L=2$ radio links are considered. The l -th link generates sessions with constant session duration and session inactivity periods that are exponentially distributed with average $1/\lambda_l$. Link #1 is associated with low-data-rate sessions ($R_{req,1}=64\text{ Kbps}$ and $T_{req,1}=2\text{ min}$), while link #2 is

associated with high-data-rate sessions ($R_{req,2}=1\text{ Mbps}$ and $T_{req,2}=20\text{ min}$).

Performance is evaluated using a system-level simulator operating in steps of 1 s under the following assumptions:

- The radio environment is modeled as a set of $P=4$ spectrum pools. The available bandwidth at each pool is $BW_1=BW_2=0.4\text{ MHz}$ and $BW_3=BW_4=1.2\text{ MHz}$.
- A simple interference model that captures the most relevant features affecting SS has been retained. A heterogeneous interference situation is considered in which the sum of the noise and interference power spectral density I_p experienced in each pool $p \in \{1, \dots, P\}$ follows a two-state discrete time Markov chain jumping between a state of low interference $I_0(p)$ and a state of high interference $I_1(p)$ with transition probabilities $P_{01}(p)$ (i.e., the probability of moving from state I_0 to I_1 in one simulation step) and $P_{10}(p)$ (i.e., the probability of moving from state I_1 to I_0), as described by Fig. 7(a). An example of the temporal evolution of $I(p)$ in a given pool p is shown in Fig. 7(b).
- Based on these probabilities, the average durations of the $I_0(p)$ and $I_1(p)$ states are, respectively, given by:

$$\overline{I_0(p)} = \frac{1}{P_{01}(p)} \quad (12)$$

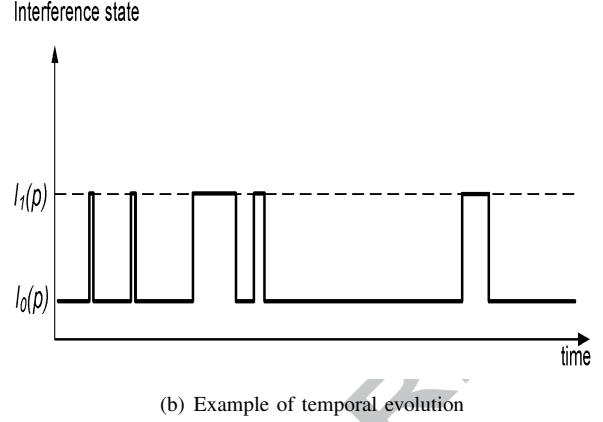
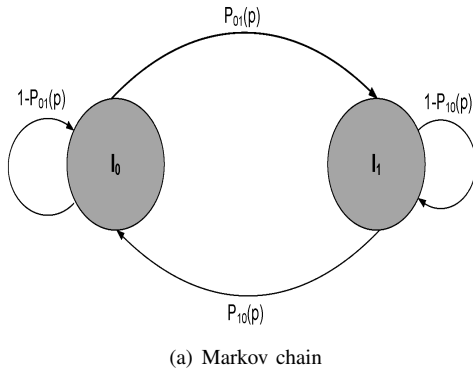
$$\overline{I_1(p)} = \frac{1}{P_{10}(p)} \quad (13)$$

- I_p evolves independently in each pool, and this evolution is independent of the traffic in the radio links. Furthermore, no mutual interference effects between different pools exist.
- In our specific case, pools #1 and #2 are always in state $I_0(p)$, while pools #3 and #4 alternate between $I_0(p)$ and $I_1(p)$ randomly with transition probabilities of $P_{01}(3)=3.7 \cdot 10^{-5}$ and $P_{10}(3)=55.5 \cdot 10^{-5}$ for pool #3 and $P_{01}(4)=1.32 \cdot 10^{-5}$ and $P_{10}(4)=9.25 \cdot 10^{-5}$ for pool #4. Based on these probabilities, the average durations of the low interference state for pools #3 and #4 are $\overline{I_0(3)}=7.5\text{ h}$ and $\overline{I_0(4)}=21\text{ h}$, respectively, while the average durations of the high interference state for pools #3 and #4 are $\overline{I_1(3)}=0.5\text{ h}$ and $\overline{I_1(4)}=3\text{ h}$, respectively.
- To smooth the short-term variability of interference conditions, $R(l,p)$ values experienced within each of the $I_0(p)$ and $I_1(p)$ states are averaged. The average achievable bit rate by one link l in pools #1 and #2 is $R(l,1)=R(l,2)=512\text{ Kbps}$, while for pools #3 and #4, the average achievable bit rate alternates between $R(l,3)=R(l,4)=1536\text{ Kbps}$ for the $I_0(p)$ state and $R(l,3)=R(l,4)=96\text{ Kbps}$ for the $I_1(p)$ state.

The system is observed during a simulation time $Sim_Time=1,000\text{ days}$. The other simulation parameters are $\xi=5$, $K=1$, $\delta_{1,p}=0.2$, $\delta_{2,p}=0.9$, $Thr_LOW=0.9$ and $Thr_HIGH=0.1$.

B. Benchmarking

To assess the influence of the different components of the proposed framework, the following variants will be compared:


 Fig. 7. Evolution of $I(p)$

- **SS**: This approach uses the proactive fittingness factor-based SS supported by only the KD (i.e., the decision-making entity of Fig. 2 is assumed to bypass the KM and retrieve only the last measured $F_{l,p}$ value from the KD).
- **SS+KM**: This approach considers the proactive fittingness factor-based SS supported by the KM module. No SM support is considered. In comparison to SS, the use of KM will allow for a better capability to track changes in the interference conditions of each pool due to the consideration of the temporal properties of $F_{l,p}$ statistics in addition to the most recent measured values.
- **SS+KM+SM**: This approach is the proposed proactive strategy in Section IV that implements the fittingness factor-based SS supported by both the KM and SM. This strategy incorporates the track-change benefits of KM together with the reallocation flexibility associated with SM.

Apart from the considered variants, the following reference schemes are introduced for benchmarking purposes:

- **Rand**: This scheme implements only the SS module of Fig. 2 and performs a random selection among available pools. Neither SM nor KM modules are used.
- **Optim**: This scheme is an upper bound theoretical reference. In each simulation step, the procedure assigns the combinations of pools and active links that maximize the total instantaneous throughput at a given time instant k as follows:

$$\max \left(\sum_{l \in \text{Active_Links}(k)} \min(R_{req,l}, R(l,p,k)) \right) \quad (14)$$

where $\text{Active_Links}(k)$ and $R(l,p,k)$ denote the list of active links and the measured bit rate $R(l,p)$ at time k , respectively. Note that this theoretical scheme assumes that the actual $R(l,p,k)$ values are continuously sent to the decision-making entity through measurement reports.

C. Performance indicators

To assess the performance of the proposed strategy, the following indicators are considered:

- The total dissatisfaction probability defined as

$$\text{Dissf} = \frac{\sum_k \text{Nb_Dissatisfied_Links}(k)}{\sum_k \text{Nb_Active_Links}(k)} \quad (15)$$

where $\text{Nb_Active_Links}(k)$ and $\text{Nb_Dissatisfied_Links}(k)$ denote the number of active and dissatisfied links (i.e., those experiencing a bit rate $R(l,p,k)$ below the requirement $R(l,p,k)$) at a given time instant k , respectively.

- The total signaling overhead in the radio interface experienced on average per link session given by

$$\text{overhead} = \frac{1}{\text{Nb_Succ_Estab} \cdot (\text{Nb_Estab_Req} \cdot \overline{\text{Estab}} + \text{Nb_Succ_Estab} \cdot \overline{\text{Release}} + \text{Nb_SpHO} \cdot \overline{\text{SpHO}} + \text{Nb_Rep} \cdot \overline{\text{Rep}})} \quad (16)$$

where Nb_Estab_Req , Nb_Succ_Estab , Nb_SpHO , and Nb_Rep denote the number of link establishment requests during the simulation duration, the number of successful link establishments, the number of executed SpHOs, and the number of measurement reports generated by the context awareness module at the terminals, respectively. The corresponding costs for establishing a link session, releasing it, performing an SpHO, and generating a measurement report by the context awareness module are set to $\overline{\text{Estab}}=266 \text{ Bytes}$, $\overline{\text{Release}}=64 \text{ Bytes}$, $\overline{\text{SpHO}}=167 \text{ Bytes}$ and $\overline{\text{Rep}}=43 \text{ Bytes}$, respectively, following the message formats given in [34].

- The SpHO signaling introduced by **SS+KM+SM** is evaluated in terms of the number of SpHOs per link session (Nb_SpHOs/session).
- The measurement reports sent from context awareness modules to the KD in Fig. 6 are evaluated in terms of the number of reported bits per second (*report signaling*).

D. Performance evaluation

This section presents the performance evaluation of the different schemes introduced in Section VI.B. The goal of this analysis is two-fold: (1) to identify which of the functional elements of the proposed architecture have the most significant impact on performance depending on the system operation

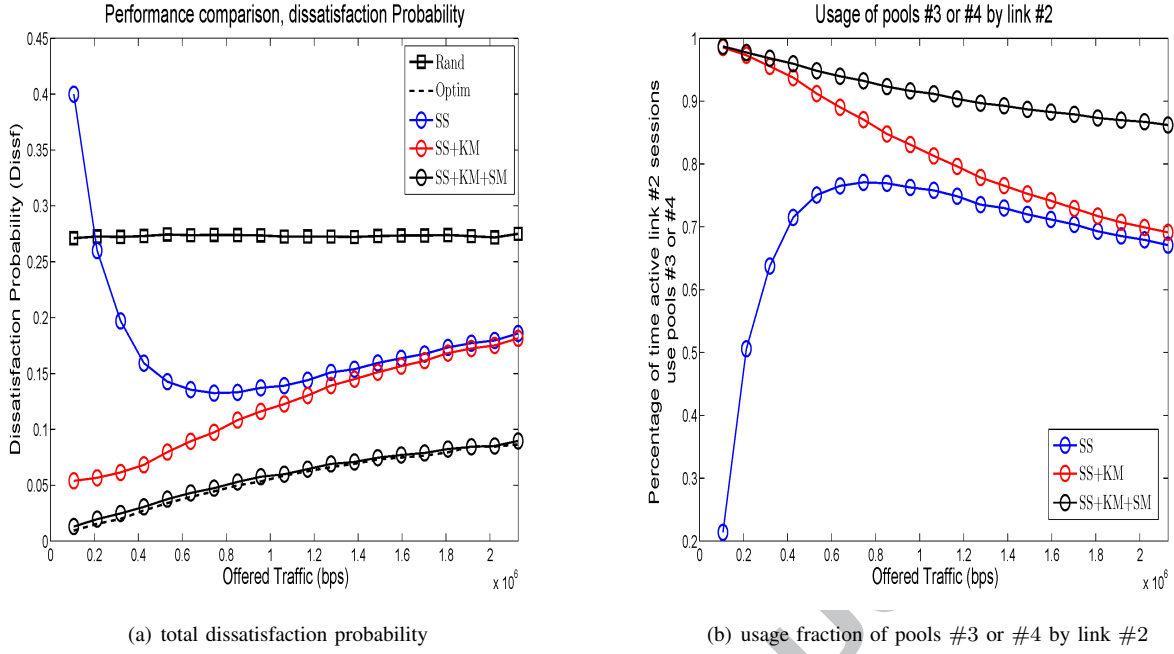


Fig. 8. SS performance comparison

conditions and (2) to benchmark the performance of the proposed spectrum management schemes (*SS*, *SS+KM* and *SS+KM+SM*) with respect to the reference *Rand* and *Optim* schemes. For all schemes, the event-triggered acquisition strategy described in Algorithm 4 is assumed.

Fig. 8(a) plots the total dissatisfaction probability (*Dissf*) defined in Section VI-C as a function of the total offered traffic load in bits per second (bps) defined as

$$\text{Offered Traffic (bps)} = \sum_l L_l \cdot R_{req,l} \quad (17)$$

where $L_l = \lambda_l \cdot T_{req,l}$ denotes the offered traffic load to link l in Erlang.

For the sake of simplicity, it is assumed that $L_1 = L_2$. Note that because link #1 is always satisfied regardless of the assigned pool (i.e., the bit rate of link #1 is always above the requirement of 64 Kbps), *Dissf* depends on link #2 only. For a better understanding of the results, Fig. 8(b) plots the fraction of time that link #2 uses pools #3 or #4 under the consideration that link #2 will be satisfied only when using these pools during the low interference state, while it will be dissatisfied whenever it is allocated pools #1 or #2 or pools #3 or #4 during the high interference state.

As seen in Fig. 8(a), when comparing *SS* against *SS+KM*, for low traffic loads below 0.6 Mbps, the introduction of KM leads to a very substantial reduction of the dissatisfaction probability. The reason for this reduced probability is that whenever interference increases in pools #3 and #4 (i.e., they move to state I_1), the corresponding measured value of $F_{l,p}$ will be LOW. As a result, the *SS* strategy that just keeps this last measured value of $F_{l,p}$ will decide in the future to allocate only pools #1 or #2, which offer a lower bit rate. Therefore, the network will not be able to exploit pools #3 and #4 moving again to the low interference state I_0 when

they become adequate for link #2. As an aside, Fig. 8(b) indicates that the fraction of time that these pools are allocated to link #2 is approximately 0.2. In contrast, the use of the KM component considers the temporal properties of $F_{l,p}$ statistics to disregard the last measured value and use an estimated value instead whenever a certain amount of time has elapsed since this last measure was taken (see the conditions of lines 5 and 11 in Algorithm 1). Correspondingly, sometime after the interference increase, the network will reallocate pools #3 and #4 to link #2, and is thus able to identify that they have re-entered the low interference state. Note that in Fig. 8(b), the fraction of time that link #2 uses pools #3 or #4 is close to one for strategies making use of KM, thus resulting in a reduced dissatisfaction probability. In summary, for low loads, KM allows for a better exploration of the different pools to identify the changes in their interference conditions, thus improving the dissatisfaction probability. In turn, when load increases above 0.6 Mbps, pools #1 or #2 will tend to be occupied by link #1 sessions most of the time, which forces the system to assign pools #3 and #4 to link #2 sessions even with reduced $F_{l,p}$. In this case, interference reductions in pools #3 and #4 are detected without the use of KM. This situation is reflected in Fig. 8(a), where the performances of *SS* and *SS+KM* are equivalent for high loads.

With respect to the role of SM, its use leads to small improvements for low loads (see the comparison between *SS+KM* and *SS+KM+SM* in Fig. 8(a)). The reason for this slight improvement is that for low loads, it is rare that a link is not allocated to the pool with the highest fittingness factor because of contention with another link. Consequently, there is no need to perform SPhOs towards a better pool except in the case when the interference increases in the allocated pool, which is responsible for the small improvement observed when comparing *SS+KM* and *SS+KM+SM*. In contrast, when

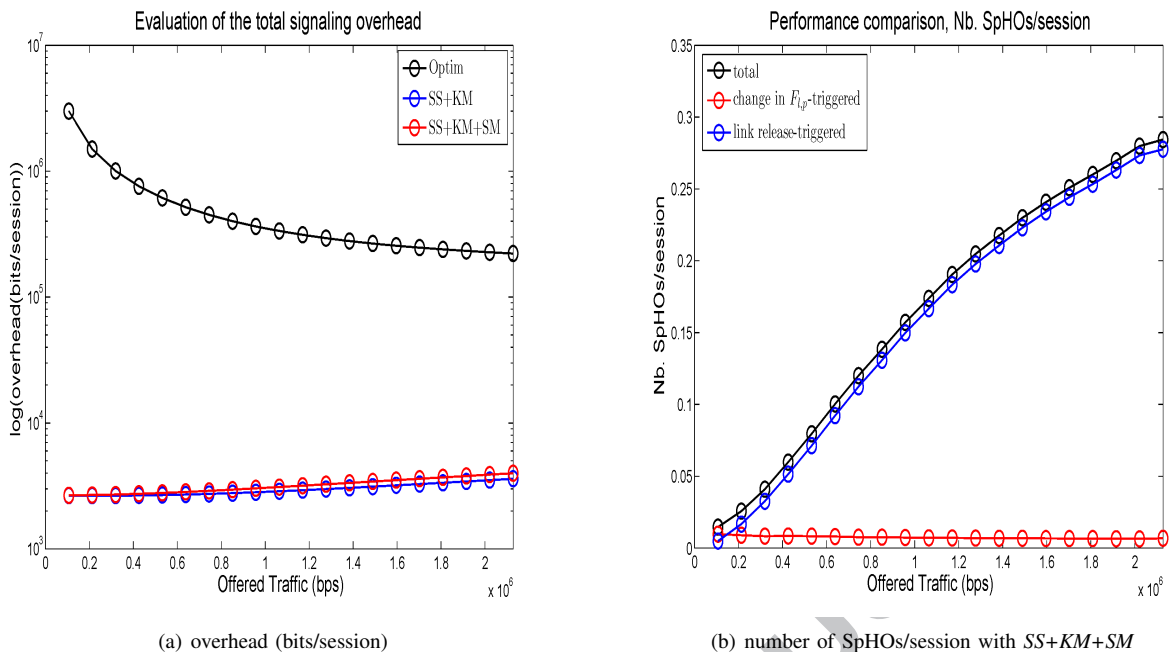


Fig. 9. Signaling cost at the radio interface in terms of

the load increases, it is more likely that the preferred pool becomes occupied by another link, and thus, a pool offering a lower bit rate is allocated. In this case, the execution of SM after the release of the link occupying the preferred pool will lead to improved performance. Note that in Fig. 8(b), with $SS+KM+SM$, link #2 is typically allocated pools #3 or #4, leading to the significant reduction in the dissatisfaction probability achieved by $SS+KM+SM$ with respect to $SS+KM$ in Fig. 8(a) for high loads.

The proposed $SS+KM+SM$ strategy performs very similarly to the upper-bound optimal scheme in terms of the dissatisfaction probability for all load conditions, mainly due to the support of the KM and SM components for relatively low and high loads, respectively. Nevertheless, the slight improvement introduced by the upper-bound scheme comes at a much higher cost in terms of signaling overhead, as will be shown in the next section. The gain observed by $SS+KM+SM$ with respect to the $Rand$ scheme (measured as the reduction in the dissatisfaction probability) ranges from 70% to 100% (see Fig. 8(a)).

E. Associated signaling cost at the radio interface

To further assess the practicality of the proposed framework, an analysis is performed on the impact of the reconfigurations performed by the SM functionality on the radio interface. The impact is evaluated in terms of the signaling overhead (*overhead*) and the amount of SpHO signaling (*Nb. SpHOs/session*) introduced in Section VI-C.

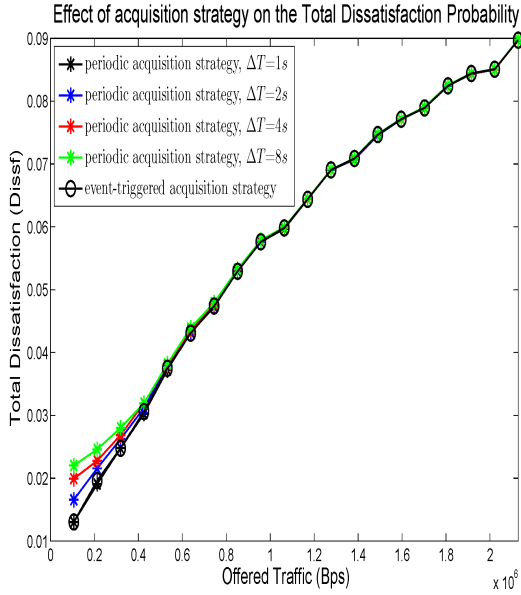
Fig. 9(a) plots the signaling overhead introduced by $SS+KM$, $SS+KM+SM$ and $Optim$ as a function of the total offered traffic load with a vertical axis in logarithmic scale for improved visualization. Fig. 9(b) plots the corresponding amount of SpHO signaling $SS+KM+SM$ is introducing for

each of the two possible triggers of SM (i.e., a link release or change in $F_{l,p}$).

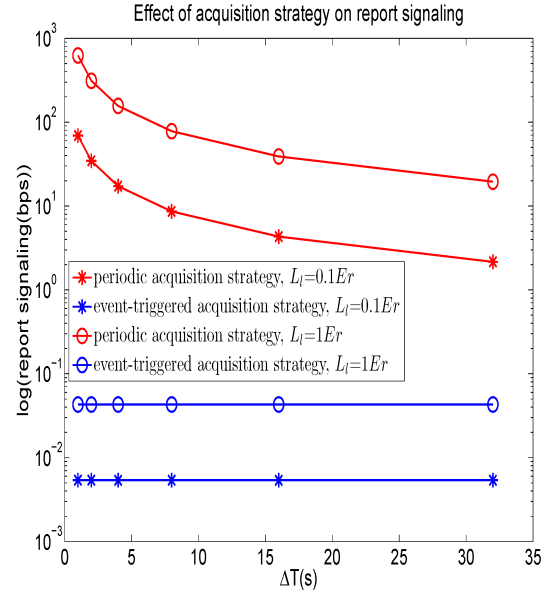
The results show that the overhead introduced by $SS+KM$ and $SS+KM+SM$ is much smaller than that of the reference scheme $Optim$ (Fig. 9(a)). This reduction is because $Optim$ requires continuously sending actual $R(l,p)$ values to the decision-making entity, which strongly increases the amount of report signaling per session, particularly for low traffic loads. In contrast, the additional overhead introduced by the proposed strategy ($SS+KM+SM$) compared to $SS+KM$ is below 10% for even a very high traffic load due to the low number of SpHOs incurred by $SS+KM+SM$ (see in Fig. 9(b) that the average number of SpHO signaling events per session is below 0.28 for all considered traffic loads). Analysis of the amount of SpHO signaling associated with each trigger in Fig. 9(b) reveals that for very low traffic loads, a non-negligible fraction of the SpHOs are triggered by changes in $F_{l,p}$ values because at such loads, links are typically assigned to their preferred pools (i.e., #1 or #2 for link #1 and #3 or #4 for link #2). As the traffic load increases, the trigger of SM by link releases becomes more relevant than the trigger due to changes in $F_{l,p}$ values and leads to more SpHO executions. This increased number of SpHO executions is because at this high traffic load, a link is more likely to find its preferred pool occupied by another link at link establishment.

F. Impact of the acquisition strategy

To evaluate the relevance of the acquisition strategy, an analysis of its impact on observed system performance versus the signaling cost is presented. The impact on system performance is evaluated in terms of the total dissatisfaction probability (*Dissf*) and cost in terms of the number of measurement reports sent from context awareness modules to the KD (*report signaling*) introduced in Section VI-C.



(a) dissatisfaction probability



(b) report signaling requirements

Fig. 10. Impact of the acquisition strategy on $SS+KM+SM$ in terms of

Fig. 10(a) plots the total dissatisfaction probability ($Dissf$) as a function of the total offered traffic load when $SS+KM+SM$ uses the event-triggered acquisition strategy (Algorithm 4). A periodic acquisition strategy sending measurements reports every ΔT (s) is also considered for comparison purposes. The corresponding cost (*report signaling*) is presented in Fig. 10(b) as a function of ΔT for different traffic loads with a vertical axis in logarithmic scale for improved visualization.

Regarding the periodic acquisition strategy, the results show that as ΔT increases, the dissatisfaction probability gets worse at low loads but remains unchanged at high loads (Fig. 10(a)). This behavior is because at low traffic loads, a non-negligible fraction of the SpHOs are triggered following a change in $F_{l,p}$ values, as previously observed in Fig. 9(b). Consequently, if ΔT is long, these SpHOs are delayed or missed, thus increasing the dissatisfaction level. As the traffic load increases, SpHOs become primarily triggered by releases of link sessions, which marginalizes the effect of increasing ΔT on the dissatisfaction probability. In contrast, increasing ΔT significantly reduces the measurement reports signaling cost, particularly for high traffic loads (Fig. 10(b)).

In summary, the results show that the event-triggered acquisition strategy outperforms the periodic approach from both the dissatisfaction probability and signaling requirements perspectives, as observed in Fig. 10(a) and Fig. 10(b), respectively.

VII. CONCLUSIONS AND FUTURE DIRECTIONS

This paper has proposed a new cognitive management functional architecture for SS. The proposed architecture integrates the fitness factor concept that tracks the suitability of available spectrum resources to support a set of heterogeneous applications subject to unknown changes in interference conditions. A set of advanced statistics capturing the hidden

dependence between the actual radio environment conditions and fitness factor behavior are retained in a KD. These statistics are used by the KM to extract the most relevant knowledge to assist in a novel proactive strategy for both SS and SM decision-making processes. The associated procedures have been described through message sequence charts. The results have shown that the proposed strategy, assisted by the KM and SM functionality, efficiently exploits the KM support at low loads and the SM functionality at high loads to introduce significant gains (ranging from 70% to 100%) with respect to a random selection and to perform very close to the upper-bound optimal scheme. The analysis of the impact of the proposed strategy in terms of signaling requirements at the radio interface has shown a significantly lower cost compared to the upper-bound optimal scheme, which strongly supports the practicality of the proposed approach.

As part of future work, it is intended to further develop the applicability of the proposed framework to decentralized scenarios, including the adaptation of decision making strategies.

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