Dynamic Channel Selection Algorithms for Coexistence of Wireless Sensor Networks and Wireless LANs

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Abstract—Due to the advances in wireless technology and spectrum scarcity, unlicensed band heterogeneous networks are growing rapidly. Increasing users of these networks should compete for the shared spectrum. Therefore, interoperability and coexistence of such networks are becoming key issues that require novel media access protocols equipped with dynamic channel selection to avoid harmful interference. In this paper we focus on dynamic channel selection for coexistence of IEEE 802.11 Wireless LAN and IEEE 802.15.4 sensor networks. Dynamic channel selection algorithm can either be implemented on top of an existing wireless sensor network or assisted with an auxiliary spectrum sensing device.

In this research couple of dynamic channel selection algorithms have been developed and implemented to evaluate the added value of the auxiliary sensing device. As such, we propose a novel energy-aware metric to detect and quantify the harmfulness of dynamic interference. We also investigated the impact of interference dynamism on algorithms performance and validated the efficiency of the implemented mechanisms by three sets of experiments. Experiments results primarily validate the efficiency of both interference mitigation techniques. Besides, these measurements suggest that the auxiliary sensing device is most beneficial for highly complex interference profiles.

Index Terms—Wireless sensor networks, ISM band Coexistence, Dynamic Spectrum Access, Cognitive Radio, Dynamic Channel Selection

I. INTRODUCTION

Advances in wireless technology have paved the way for the emergence of new wireless standards in ISM band where they should compete for the common spectrum. Therefore, interoperability and coexistence are major issues that must be solved for such heterogeneous networks. IEEE 802.11 Wireless LAN and IEEE 802.15.4 personal area networks (PAN) are examples of ISM band networks with highly dissimilar transmission profiles in terms of coverage, bandwidth, output power, and application requirements. The output power of IEEE 802.15.4 devices is usually lower than 0 dBm [1], while the output power of IEEE 802.11 devices is typically 15 dBm or higher [2]. Spectrum utilization is another dissimilarity where according to the standards, each IEEE 802.11b/g channel occupies at least 4 contiguous IEEE 802.15.4 channels [3].

Application-wise, sensor networks are not demanding in terms of throughput. However, they require high reliability and robustness against attacks or unknown events in case of monitoring applications. In contrast, IEEE 802.11 networks are typically used by a limited number of throughput-intensive applications. Moreover, mobility is one of the most important characteristics of most IEEE 802.11 devices which adds spatial dynamism to the interference profile of the environment.

Additionally, new broadband Internet services and applications for advanced WiFi-enabled devices such as smart phones and tablets are attracting more users every day. The high bit rate of novel IEEE 802.11 interfaces and throughput demanding applications all result in burst WiFi traffic which occupies the channel at least an order of magnitude more than a single IEEE 802.15.4 packet. In presence of such WiFi traffic, due to their CSMA/CA mechanism, sensor networks easily enter a blocked state where they are prevented from packet transmission. Consequently, the packet success rate drops drastically as evidenced in our observer reference experiment in section IV. This is why the performance of the sensor nodes communication links is compromised when they are present in environments with a broadband WiFi Internet connection.

Packet loss is a major issue in wireless sensor networks and directly degrades robustness and energy consumption, two performance metrics of great significance in this context. When a packet is lost in connection-oriented applications, it should be retransmitted to the receiver. Power consumption specifications of CC2420 which is a frequently used IEEE 802.15.4 radio front-end [1], show that a node transmitting or receiving radio packets consumes at least 20 times more power than when it is in low power mode. Thus, high packet error rate (PER) should be avoided on battery constrained wireless sensor nodes. Moreover, in time-sensitive applications such as monitoring and alarm systems, every packet is valuable and it is crucial to preserve data from being lost due to interference.

The IEEE 802.15.4 standard proposes channel selection algorithms to be performed by the network coordinator at network initialization; however no specific implementation guideline has been suggested. This mechanism is helpful for static interference profiles, given that the algorithm investigates the interference effectively. With the IEEE 802.15.4e standard [3] time slotted channel hopping (TSCH) MAC has been released which facilitates more efficient coexistence and spectrum management. Many algorithms have been developed
in literature to find the best channels at initialization or periodically at specific time intervals. For instance in [4] all channels are scanned and classified according to their interference level and activity, and then the best channel is selected by the coordinator and all other nodes are reassigned to this channel by a control message. In [5] different channels are used to transmit and receive packets. The idea is that the network coordinator assigns to a node the channel with the lowest PER as the receive channel while all nodes should be informed of the receive channel of other nodes. Both aforementioned algorithms spend some amount of time and energy to find the best channel per node. Moreover, they do not react against dynamic interference as they are one-time algorithms and the communication link is not assessed during the packet transmission.

There are also theoretical channel selection algorithms based on reinforcement learning. For instance in [6] a distributed algorithm has been proposed where converging to a single channel and finding a balance between exploring channels to assess them and staying on a channel is the aim of the algorithm. This algorithm has been improved in [7] where the outcome was a more robust strategy to balance the exploration and exploitation of the channels. Lack of implementation is the drawback of both algorithms while they have the advantage of being distributed, in the sense that a central entity or network coordinator is not required to survive the network in presence of extreme interference.

Increased awareness of the environment on a broad frequency range is however costly. Many solutions rely upon the availability of a separate radio that is optimized for spectrum scanning [8]. Adding such extra hardware might not always be acceptable when the dynamic channel selection is implemented on top of an existing solution. In order to react timely to channel utilization variations, the scanning operation needs to be performed continuously resulting in a very large extra energy cost for the wireless device.

The objective of this work is to compare interference mitigation approaches with and without exploiting a wide band spectrum sensing agent by implementing the algorithms in living wireless test-bed. We will investigate several channel switching algorithms to evaluate the added value of using a sensing agent on top of an existing wireless sensor network. We will also investigate control data overhead of channel hops per each scenario. In contrasts to similar approaches in literature, all of our algorithms are designed to tackle the dynamic interference rather than only a static interference profile.

The organization of the rest of this text is as follows. In section II we develop our theoretic approach based upon several experiments and the idea of using three performance parameters namely, Busy, Success, and Failure. Subsequently, the implementation is elaborated in section III. Section IV demonstrates the results of experiments we performed to support our theoretical vision. Finally, section V concludes this paper.

II. Solution

In this study, similar to other cognitive solutions, interference mitigation strategy has three steps: link information acquisition, link assessment, and decision making. The solution is centralized i.e., regardless of the approach in any of these three steps, link assessment and decision making is performed by a central entity or processing unit. The central entity may have more than one radio interface to facilitate simultaneous communication on different channels at different locations.

A. Link information and Communication Protocol

There are two sources for link information acquisition: the IEEE 802.15.4 nodes themselves, and a single “sensing device” which is capable of reporting the spectral power level of all sixteen IEEE 802.15.4 channels with an acceptable temporal resolution. Although the former provides better spatial information since nodes are installed at different locations, every node at any moment can merely sense a single channel. On the other hand, the sensing device monitors all channels at any time, yet no spatial information can be expected. While the sensing device only gives the sensed power levels, the IEEE 802.15.4 nodes can provide other type of link quality information such as back-off rate.

Wireless sensor networks are mostly intended for environment monitoring applications where they produce sensing data periodically with an application-dependent time period. Therefore, without losing generality, we suppose that every $T$ second, a node enters the active mode to send its message to another node or relay other nodes messages. Each message comprises a number of packets. The transmitter uses automatic repeat request (ARQ) mechanism for error control as illustrated in Figure 1. We define Success, Busy, Reattempt and Failure terms to develop the energy model for this communication protocol.

![Communication protocol](image)

**Success**: happens when the transmitter receives an ACK for a sent pack. Subsequently it moves on to the next packet if there is any to send.

**Busy**: is equivalent to CSMA/CA back-off. Number of back-offs at transmitter increases when a back-off occurs. Note that according to the IEEE 802.15.4 standard [3], acknowledgment packets do not exploit the CSMA/CA mechanism.
Reattempt: transmitter restarts the CSMA/CA mechanism which allows macMaxCMABackoffs [3] consecutive back-offs for one packet and tries to send the same packet again. macMaxCMABackoffs [3] can have integer values between zero and five inclusively. In our experiments we set macMaxCMABackoffs [3] equal to five.

Failure: occurs when the transmitter does not receive an ACK for its previous packet within a certain time. As a result, message duration increases by an ACK-timer period. Transmitter retransmits the same packet.

According to the model which should be acquired from the IEEE 802.15.4 nodes are the number of back-offs and acknowledged packets. Using ARQ mechanism, these measured values are all available at transmitters.

We will also use spectrum power samples from the sensing device as another Link Quality Indicator (LQI). Note that this sort of link information is independent of data flow and communication protocol.

B. Link assessment

1) Assessment by IEEE 802.15.4 nodes: Large difference of active and idle mode power consumption of typical IEEE 802.15.4 radios such as CC2420 [1] necessitates the battery constrained nodes to stay in low power mode as often as possible. Here we develop a model for energy degradation of the node in presence of interference according to the power consumption of active and low power modes. Considering the communication protocol explained in section II-A and active and passive durations, we will quantify the energy degradation by defining the following parameters.

$T$ is the expected value of inter-message period. $P_a$ and $P_p$ are power consumption of active and low power mode respectively. In this model, $T_m$ is defined as duration of a message which is transmitted in ideal interference-free condition where no back-off or failure occurs. $T_a$ is the estimated time the node actively transmits its packets. The extra active time burden caused by interference is therefore the difference of $T_a$ and $T_m$. When a back-off occurs before next retry, the node waits for $T_{bf}$. In case of a failure, the node remains active for a time equal to the time of a successful packet transmission to the receiver and receive of its corresponding ACK which we denote by $T_{ack}$. We denote the successful packet time for a transmitter by $T_s$. The average power consumption $P_{avg}$ of a node is calculated as:

$$P_{avg}(T_a) = \frac{T_a}{T}P_a + (1 - \frac{T_a}{T})P_p$$  \(1\)

Hence we can define Relative Power Degradation $RDP$:

$$RDP = \frac{P_{avg}(T_a) - P_{avg}(T_m)}{P_{avg}(T_a)}$$  \(2\)

Substituting $T_a - T_m$ and $T_m$ with the corresponding so called Busy, Failure and Success parameters in equation 2 yields:

$$RDP = \frac{Busy \times T_{bf} + Failure \times T_{ack}}{Success \times T_s + T_p \frac{P_p - P_a}{P_a}}$$  \(3\)

$RDP$ in equation 3 is used as our metric to determine the optimum time of channel change in our experiments.

In practice for a transmitter as the initiator of a communication, $T_a$ should be limited to an upper bound, i.e. there must be a limit on retransmissions. Let us take $T_{a,max} = (1 + k) \times T_m$ where $k$ is an extension parameter. If a transmitter cannot send its message in $T_{a,max}$ the message must be discarded. This constraint requires the average $Success$ to $Total$ attempts ratio during $T_a$ to be higher than

$$\left(\frac{Success}{Total\ Attempts}\right)_{\min} = \frac{1}{1 + k}$$  \(4\)

such that the transmitter transmits its message flawlessly.

RPD is a basic metric which only considers a single link. It does not model network level characteristics such as impact of different links on each other. For instance, overhearing is one of the major factors of energy waste [9] that can keep a node in receive mode that is not considered. On the other hand, due to its generality it can easily be utilized both in the centralized and distributed algorithms and its simplicity makes it feasible to implement. The fact that in derivation of RPD attention has been paid to the role of busy may indicate that this metric is Transmitter based since the parameter busy is not meaningful to a receiver. However, during a message transmission, the transmitter and the receiver are in active mode for rather the same period. Therefore, while not considering the precise active duration of the receiver, RPD represents an acceptable estimate of its energy overhead.

2) Assessment by an auxiliary sensing device: For the purpose of link assessment by the sensing device we used the number of samples which exceeded a certain threshold within the most current window interference power samples in order to select the best channel.

The final result of the link assessment is a channel ranking table for each link, per each metric. The elements of the ranking table are all channel numbers, ordered from the highest metric value to the lowest, together with their corresponding metric values. Using these ranking tables of the two sources, the processing unit generates the final ranking table which is then passed to the last step of decision making. Each link now has its own ranking table and channel numbers can be assigned to every active transmitter/receiver pair.

C. Decision making

The decision engine will select one of the two following policies. First policy will set an RPD metric threshold and proceed to channel change only when the measured metric value of the current channel becomes greater than the threshold. This type of decision increases system stability yet introduces latency in proper reacting to the dynamic interference. The second policy follows the best channel proposed by the auxiliary sensing engine which in theory should bring better results although requires more channel management effort.

D. Algorithm evaluation

The system level analysis of the experiments necessitates definition of new terms. Thus, Packet Failure Rate (PFR) is the percentage of failed attempts. There are two major differences between PFR and its similar concept, PER. PER
is defined for a transmitted packet whereas PFR is defined for an attempt. In systems with acknowledgment, a successful attempt is accomplished when a transmitter receives the ACK of its previously sent packet. Thus in addition to the corruption of the original packet, failure in receiving its ACK also contributes to PFR. Besides, a failure in an attempt can be the result of other issues such as several back-offs followed by a discard while PER is meaningful for a packet which has passed the CSMA/CA phase.

Optimizing WSN communication in this context is more practical on message level than packet level. Hence, we use Energy Waste Per Message (EWPM), Message Failure Rate (MFR), and Channel Change Per Message (CCPM) as our yard stick to evaluate cognitive mechanisms. EWPM is the ratio of difference between the total consumed energy and the ideally expected energy to the total number of successful messages. MFR is the percentage of unsuccessful messages. The communication link is used whenever a message is transmitted. Hence it is useful to monitor the average number of channel shifts for a single message which we refer to as CCPM. We calculate CCPM by dividing the number of channel shifts to the total number of messages. In our implementation which is explained in section III, channel shift opportunity equals the number of messages which limits CCPM to the range zero to one.

III. IMPLEMENTATION

In this research we used the iMinds WiLab.t test-bed at Gent University. WiLab is an experimental, generic, and heterogeneous wireless test-bed deployed in the iMinds office building [10].

When processing the reports we used the metric parameter values 1,26,26,30000 milliseconds for \( T_{ack}, T_{ack}, T_{r}, \) and \( T \) respectively. The value of \( \frac{P_0}{P_{TH}} \) is set to 50. These assignments are based upon the practical requirements, our scenario, and technical specifications ([11], [11]).

Interference dynamism is meaningful when compared against the frequency of link quality reporting. When the interference profile changes faster than the reporting frequency, most solutions cannot mitigate its adverse impact. In practice, even if the reporting frequency was high enough, channel management for a very dynamic link may not be feasible.

In our experiments we guaranteed a duration for which interference profile was constant. This duration had average value of \( \text{interference duration mean} T_i \) and had a uniform variation range of \( \pm 10\% \times T_i \). With this assumption, we defined Dynamism \( D \) as

\[
D = \frac{T_r}{T_i}
\]

where \( T_r \) is the reporting period and equals the messaging period \( T \).

The ten percent variation over \( T_i \) along with the randomness of inter-message time, reduce the probability of the constant relative phase between interference profile variation and link quality sampling. In all experiments we selected \( T_i \) of 30 seconds, IEEE 802.15.4 packet length of 120 bytes, number of packets per message equal to 100, the IEEE 802.11 packet rate and packet size of 1 Mbps and 1240 bytes respectively.

IV. EXPERIMENTS

Based upon the theoretical approach explained in section II, we executed several experiments to examine the effect of interference as well as addressing the added value of an extra sensing device. Several link level and a network level experiment are described in this section where they have been evaluated with the aforementioned CCPM, MFR and EWPM metrics.

A. Link level experiments

We organized link level experiments with one and two sources of interference. After staying in one of the three IEEE 802.11 channels of 3, 7, and 11 for about \( \frac{T}{D} \), each interference source switches again to a random channel out of the three channels. The interference sources are not mutually synchronous. The intention of these experiments is to study the impact of dynamism on the performance of cognitive algorithms and consequently examining the added value of exploiting a spectrum sensing engine. The interference output power is set to 15 dBm, and packet rate is 90 packet/sec which occupies the channel to a great extent. For the two link level experiments \( k \) (retransmission extension parameter) equals 2.

1) Impact of the interference dynamism: Figure 2 demonstrates the floor plan of the WiLAB third floor where all experiments were executed. We put the IEEE 802.15.4 link from node 30 to node 31 under interference by the IEEE 802.11 traffic generated with node 29.

In order to compare algorithms with a reference scenario, before running experiments, we first executed an observer scenario. In this experiment node 30 was producing periodic messages while it was constantly on IEEE 802.15.4 channel 18 and the single random interference source was present on the full overlapping IEEE 802.11 channel 7.

For the next step we executed scenarios with dynamisms of \( \frac{1}{3}, \frac{1}{3}, \frac{1}{3} \), and 1. When the relative power degradation threshold was exceeded, transmitter and receiver would hop to the next channel meaning that the nodes would circulate clockwise between channels 14, 18, and 22. In this experiment because only one interference source was introduced to the system, the assumption was by changing its current channel a link should end up in an acceptable channel. This facilitates studying the impact of interference dynamism and time domain factors on the cognitive mechanism efficiency.

According to the the results documented in table I, when interference profile is highly dynamic, the link has to switch its channel more often but still it does not gain in energy or performance as it gains for less dynamic interference.
However, even in the case of 1 for the dynamism, Energy Waste Per Message (EWPM) and Message Failure Rate (MFR) are much lower than that of the system with fixed channel. Obviously as expected the interference dynamism plays a drastic role on the performance of the IEEE 802.15.4 link.

<table>
<thead>
<tr>
<th>Dynamism</th>
<th>No-Hop Sys.</th>
<th>1/2</th>
<th>1/3</th>
<th>1/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFR [%]</td>
<td>26</td>
<td>19.63</td>
<td>16.37</td>
<td>11.44</td>
</tr>
<tr>
<td>EWPM [%]</td>
<td>92.35</td>
<td>65.11</td>
<td>51.77</td>
<td>34.48</td>
</tr>
<tr>
<td>CCPM [%]</td>
<td>0</td>
<td>32.08</td>
<td>16.43</td>
<td>11.48</td>
</tr>
</tbody>
</table>

**TABLE I**

ENERGY AND PERFORMANCE RESULTS OF SINGLE INTERFERENCE SOURCE EXPERIMENTS WITH \( k = 2 \).

2) **What is the added value of a sensing engine?:** Using nodes 28 and 29 as the sources of interference, we made at least one and at most two out of the three IEEE 802.15.4 channels 14, 18, and 22 intentionally interfered. The interference dynamism of each of the two sources was 1/4. In this situation switching to the next channel does not guarantee the new channel to be clear. As a result, for selecting a new channel an intelligent approach is required that has a knowledge of other channels. Unlike the previous experiments set, here we exploited the IMEC Sensing Engine [12] to acquire spectrum information. The setup of this scenario is the same as the last experiment with the sensing engine installed at node 24. We ran an experiment with two random interference sources on a static channel link. Its results serve as a reference to evaluate the efficiency of the spectrum aware mechanism. Besides that with the same configuration we also executed an experiment without using the sensing engine where interference mitigation was done only by switching channels.

Indeed the simple strategy of switching to next channel is not as efficient as it was in single interference source experiments. We utilized IMEC SE in the same way explained in II-B2. The SE was evaluating the channels based on their history of last 30 seconds. According to table II that demonstrates the overall results of double interference source experiments, using sensing engine does not pay off dramatically when interference is not intense in most channels.

<table>
<thead>
<tr>
<th>Exploration</th>
<th>None</th>
<th>Without SE</th>
<th>With SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFR [%]</td>
<td>50.19</td>
<td>26.1</td>
<td>22.85</td>
</tr>
<tr>
<td>EWPM [%]</td>
<td>262.54</td>
<td>92.22</td>
<td>77.79</td>
</tr>
<tr>
<td>CCPM [%]</td>
<td>0</td>
<td>26.2</td>
<td>22.91</td>
</tr>
</tbody>
</table>

**TABLE II**

ENERGY AND PERFORMANCE RESULTS OF DOUBLE INTERFERENCE SOURCE EXPERIMENTS. \( k = 2 \).

B. **Network level experiments**

As a very basic network we used three links of transmitter nodes 25, 26, 30 to receiver nodes 27,28, and 31 respectively. These three links did not exchange data. The only reason we refer to them as a network is that the decisions made by the central processing unit is based on the information gathered from all of them. Therefore a report from one link may change the channel for another link. We projected the whole network with an interference generated jointly with 6 sources of nodes 13,15,21,41,42, and 44. Each source dynamically changed its profile. Tunable interference profile parameters were output power, operating channel, and packet rate. Output power was 10 to 15 dBm. Operating channel was any of IEEE 802.11 channels available in Europe (1 to 13). Packet rate was one of 10, 20, 45, and 90 packets per second. The duration of remaining in a certain profile was between 30 and 60 seconds which leads to dynamism of 1 down to 1/2. All these parameters and also profile duration were random, with uniform distribution. They were assigned at every ending of a profile period. Using several interference sources helps us to have more dynamic environment and also variety of metric values to evaluate metric efficiency. As with the previous experiments, a none exploring system was first tested under this interference. The link was on IEEE 802.15.4 channel 18.

The reports of every node was monitored and processed by a central entity. Whenever a channel was reported to have RPD higher than 0.3 by any of the transmitters, the following communication link was established in another channel indicated by the SE. Here also time window of the SE was 30 seconds. Finally, as the last experiment we ran the same scenario with a different policy where channel switching was not triggered by exceeding the threshold, rather the links always tried to reach the best channel. This approach requires a comparative measure of relative channel metric values. Nevertheless because of a diverse and fairly heavy interference present in the whole spectrum and also because of reasonably large SE time window (30 seconds), the risk of fluctuating between two very good channels is low.

The result of this set of experiments is documented in Table III.

<table>
<thead>
<tr>
<th>Exploration</th>
<th>None</th>
<th>Threshold based</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFR [%]</td>
<td>23.98</td>
<td>11.76</td>
<td>6.22</td>
</tr>
<tr>
<td>EWPM [%]</td>
<td>79.68</td>
<td>35.73</td>
<td>18.12</td>
</tr>
<tr>
<td>CCPM [%]</td>
<td>0</td>
<td>21.4</td>
<td>23.96</td>
</tr>
</tbody>
</table>

**TABLE III**

ENERGY AND PERFORMANCE RESULTS OF NETWORK LEVEL EXPERIMENTS. \( k = 2 \)

With only about 10 % extra channel switching in continuous exploration scenario compared to threshold based one, significant improvement is achieved in both EWPM and MFR. This indicates that wireless environment is highly dynamic and sluggish adaptation wastes chances of optimization to a great extent.

Figure 3 illustrates the EWPM and MFR curves that are extrapolated on the \( k \) parameter based on the outcome of the measurements in network level experiments with \( k = 2 \). These curves imply that the static system is more sensitive to the parameter \( k \). This was expected because the other mechanisms set system in more clear channels with lower PFR.
interference profile is complex. Moreover, this research proves the feasibility of efficient standalone dynamic channel selection algorithms. For the link level experiments with one interference source and their dynamism are limited.

V. Conclusion

To tackle the harmful dynamic interference of IEEE 802.11 networks we developed a power degradation model for the operation of IEEE 802.15.4 nodes. The huge difference of low power mode and active mode power consumption of IEEE 802.15.4 radio front-ends is the main idea for derivation of power degradation from the number of back-offs as well as successful and failed packets.

To support this model we implemented our own custom tailored software infrastructure. We devised several scenarios to run several link level and network level experiments at iMinds WiLAB test-bed at Gent university. Moreover, we formulated the interference dynamism to study its influence on the performance. Experiments results revealed that interference dynamism plays a significant role in the performance of cognitive algorithm. For the link level experiments with one interference source 6% to 16% can be gained in message failure rate while energy waste per message decreases 27% to 62% depending on the interference dynamism. In the scenario with two sources of interference by exploiting a wide-band sensing engine we gained 28% in message failure rate and 185% in energy waste per message. The same scenario without sensing engine brought about 24% and 170% in the aforementioned performance and energy yard sticks.

On the network level, scenarios were developed to evaluate the two strategies of persistent exploration versus exploration in case of exceeding the threshold. The results of experiments express 17.7% gain in performance and 61.5% in energy waste per message for the former and 12% gain in performance and 44% in energy waste per message for the latter.

These measurements suggest that the auxiliary sensing device may be advantageous when the interference profile is complex. Moreover, this research proves the feasibility of efficient standalone dynamic channel selection algorithms on top of existing wireless sensor networks given that the interference sources and their dynamism are limited.

References


