DYNAMIC SPECTRUM ACCESS ASSESSMENT IN COGNITIVE RADIOS

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ABSTRACT

The opportunistic utilization of unused spectrum provides Cognitive Radios (CR) with great performance improvements and enables new applications and services. This Dynamic Spectrum Access (DSA) behavior, however, introduces several challenges that must be overcome before CR technology can be widely deployed. One of these problems is the assessment of DSA compliance with regulations and policies. Traditional techniques used to validate and evaluate the performance of communication systems are no longer sufficient due to the extreme flexibility and independent decision-making inherent to CR. New test and analysis methods need to be developed to assess the spectrum access behavior of CR and safeguard the harmonious interaction with other CR and legacy systems.

In this paper, we propose a test strategy for assessing the DSA behavior in CR. Candidate measurement techniques, operational scenarios, and test beds to assess the correct functionality and performance of CR are presented. This paper explains the application of these techniques in the context of a CIREN prototype, an ongoing development effort at Virginia Tech as part of the Smart Radio Challenge. The techniques here described provide an initial set of guidelines for regulatory bodies and radio developers to assess the DSA capabilities of CR devices.

1. INTRODUCTION

Of the many features that make Cognitive Radios (CR) a topic of great interest to researchers, the opportunistic utilization of unused spectrum currently drives the most attention and inquiry. One of the first applications envisioned for CR technology is the utilization of unused spectrum by featuring dynamic spectrum access behavior (DSA). As defined in the IEEE p1900.1 Draft Standard, dynamic spectrum access is:

> *(a) The near-real-time adjustment of bandwidth utilization and spectrum resource usage in response to changing circumstances and objectives, including interference experienced or created, changes of the radio's state (operational mode, battery life, location, etc.), changes in environmental/external constraints (spectrum, propagation, operational policies, etc.), and/or in response to a received command.*
>
> *(b) Technique by which a radio system dynamically adapts to select operating spectrum to use available (in local time-frequency space) spectrum holes with limited spectrum use rights.*

Although radios with DSA capabilities have clear benefits such as increased data rates, they may also create conflicts. One of the main concerns about the deployment of such technology is the possible disruption of deployed networks caused by misbehaved secondary users. In order to prevent this, regulatory and standardization bodies are working to provide a comprehensive set of regulations that rule the operation of these devices. Unfortunately, laying down the rules is not enough; we have to ensure that DSA-capable radios comply with them.

While many techniques exist for assessing the spectrum access behavior of traditional radios, they are designed for static devices that can only operate in predefined frequency bands limited by hardware. Due to the extreme flexibility envisioned in CR, it is necessary to tailor test and analysis methods to assess their spectrum access behavior and safeguard the harmonious interaction with other systems.

In this paper, we propose a test strategy for assessing the DSA behavior in CR. We present this strategy in the context of the Cognitively Intrepid Radio Emergency Network (CIREN), an ongoing development effort at Virginia Tech as part of the Smart Radio Challenge. This strategy includes the test case definition approach as well as candidate measurement techniques, operational scenarios, and test beds required to execute the test cases identified. We briefly describe the CIREN protocol, introduce the test strategy, and present the application of our strategy to define test cases.

2. SYSTEM DESCRIPTION

Because test case generation depends on the specific characteristics of the system under test, we need a target system to be used as a reference. The operating principles of the system under consideration were first described as part of Team MPRG's technical proposal submitted to the SDR Forum Smart Radio Channel [4]. It is an agile sommunication system that automatically establishes data links in the licensed family radio service (FRS) [1] band to support first response teams following major disasters, while avoiding primary users and interference. The DSA aspects of the CIREN protocol are briefly described here for clarity. Issues not directly related to spectrum access, such as operating modes and cognition mechanisms, are not discussed.

2.1. CIREN Protocol

This protocol describes how CIREN radios operating in the FRS band establish and maintain data links. The radios operate in a master/slave mode with either a point-to-point connection, or in a voice/video broadcast mode. There is no base station or reliable control channel in this approach.

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Therefore, the master and slave nodes must rendezvous using spectrum sensing techniques. Generally, in these situations, the server and/or client nodes transmit beacon signals to establish the link [7]. Because the FRS band has only 14 allocated channels, the master node transmits a special bit pattern as a beacon signal directly to the slave node, without the use of a base station. The rendezvous process is quite possibly the most critical aspect of the system because of the necessity to share the spectrum with incumbent/primary users entering and leaving the FRS channels in a stochastic manner.

2.1.1. Beacon Signal: Each node is assigned a 63-bit psuedonoise sequence [6] that serves as the node's network-wide unique identifier (UID). When attempting to connect to another radio, the master node transmits the slave node's UID in repetition 56 times using BPSK modulation. Following this beacon signal, the master node sends a preamble synchronization pattern, also using BPSK (see Figure 1). While not connected, each receiver scans the 14 FRS channels looking for data signals and gathering information about channel quality. If a BPSK signal is found, it demodulates and correlates the resulting soft decision bit sequence with its own UID m-sequence (and a special m-sequence for voice/video broadcast mode). If the magnitude of the correlator output is high, the signal is a beacon intended for them. Otherwise, after a short time, the receiver will move on to the next frequency (see Figure 2). This scanning process also allows for the radios to determine which channels are available or, if occupied, what type of user in which the channel currently resides.

This data-gathering process is fed into a radio environment map (REM) database [8] for the cognitive radio controller to use for choosing a candidate transmission channel when the user requests a data link. Once the link is established, the radios switch to higher modulation schemes to improve spectral efficiency.

2.1.2. Preamble Synchronization: Following the beacon, a preamble synchronization packet is transmitted that contains link information from the master node including its own UID, intended destination (slave node UID), operational mode, and a secondary backup channel in case the current one becomes unavailable. This secondary channel mitigates problems with service delay, particularly in modes such as streaming audio and video where latency is a critical issue.

2.1.3. Synchronization and Confirmation : Upon reception of the preamble synchronization packet, the slave node replies with a synchronization reply packet including acknowledgment (ACK/NAK) and some additional verification information including channel state data, supported modes, and power control information. Finally, the master node emits a confirmation packet at which time the link is established and the master node can begin pushing data.

2.1.4. Maintaining the Connection: Once the connection is made, both radios collaborate to maintain it. Ultimately it is up to the master node to make any adaptations. As long as the channel remains unoccupied by incumbent FRS users, the data radios can continue to use it. However as soon as the channel becomes occupied, the link needs to be established on another channel. The CIREN radios periodically sense the channel looking for primary FRS users co-operating in the same channel. This happens during so-called "quiet times" where both the master and slave nodes stop transmitting and analyze the spectrum. If a primary user is found the nodes revert to a pre-determined backup channel in order to maintain the link.

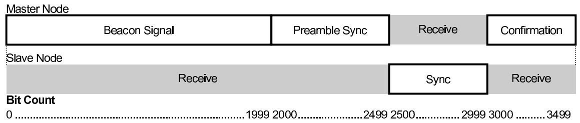

Fig. 1. Bit sequence used to rendezvous and establish CIREN connections. The sync. and confirmation packets are not used in voice/video broadcast.

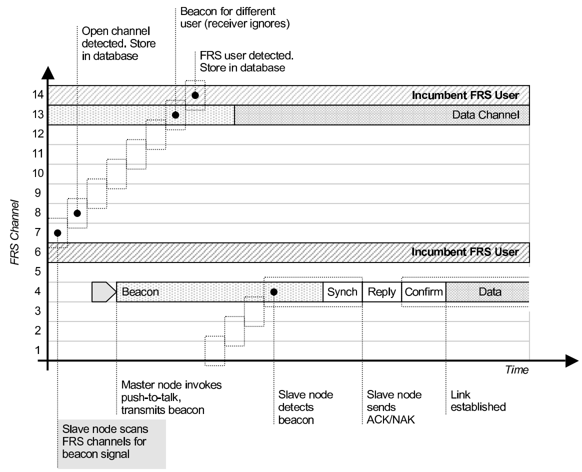

Fig. 2. Example of spectrum access behavior of the CIREN system

3. TEST STRATEGY

From the description of the protocol, we get an idea of the complex logical relations that exist in terms of control structures. Furthermore, the implementation will likely include a flexible RF front end controlled mainly by software. Because of this, a mixed testing approach is used in the validation efforts including traditional software testing techniques along with traditional radio measurement techniques.

In this test strategy we outline the procedure to define test cases based on functional (black-box) [3] analysis at the system level as part as the validation effort. Some of these test cases can be applied at lower levels and help with the development of individual modules. It is important to note, however, that these test cases are defined independently of the implementation, thus avoiding any bias.

While many aspects of a cognitive radio must be thoroughly tested, in this test strategy we only address features related to dynamic spectrum access. The techniques proposed and followed here are aimed at assuring policy compliance from a regulatory perspective.

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The proposed general testing strategy is an adaptation of [5] and includes the following steps:

1) **Identify intependent testable features**. Decompose the system into distinct features that can be tested separately. This task is different from module decomposition and simplifies the test generation problem and eases the location of faults
2) **Define equivalence classes for each feature**. Identify partitions in the input domain where values are expected to be treated similarly by the implementation. This tasks helps reducing the number of test cases by decreasing test case redundancy
3) **Use boundary value analysis and decision tables when appropriate to identify test cases [3]**. Select the specific nominal, boundary, and erroneous values that define the test cases. If there are complex logical relations in the feature under test, we use decision tables to mechanically force a comprehensive set of test cases.
4) **Create test cases**. Generate the execution environment defined by the input values for each test case identified.
5) **Execute and report**. Run the tests and capture and report the results

4. INDEPENDENT TESTABLE FEATURES

In this section we describe each independent testable feature identified as well as the test case selection process and the infrastructure required to execute them. Due to the experimental nature of the target system and the lack of specific regulatory limits in terms of DSA, the test results are limited to the evaluation and characterization of system performance. Due to space limitations, features such as quality of service requirements are omited from the analysis. The validation of the spectral characteristics of the system (e.g. peak transmit power, power spectral density, emissions bandwidth, out-of-band emissions) is not treated in this project. For more information on these issues see [2] and related documents.

4.1. Scanner

The scanner module is responsible for the detection of radio signals in the FRS band. Once a signal is detected, the scanner is also required to classify it as an incumbent user or a CIREN transmission.

For the scanner module, three independent testable features are identified:

1) **Sensitivity.** The weakest signal level detected by the system.
2) **Channel occupancy detection.** The ability to detect if a channel in the FRS band is occupied or not
3) **Signal classification.** The ability to identify the nature of the signal detected (Incumbent user or CIREN transmission). Because this feature is not scheduled to be completed in the first version of CIREN, we ommited the test case analysis for it.

4.1.1. Sensitivity: The goal of this test is to identify the minimum signal level in a channel that is labeled as occupied. Because there is no actual sensitivity requirement, the output of this test is just a characterization. It is important to note, however, that if this level is higher than the minimum signal level demodulated by an FRS radio (P_{FRS_min}), then there is great potential for interference to the primary users.

a) Inputs and domains: The actual scanner input is a stream of antenna samples. However, for this test we can define three logical inputs:

- **Channels [1,14]**: The set of FRS channels scanned.
- **Signal level [-100 dBm to -40 dBm]**: The lower limit is defined by the noise level in our spectrum analyzer, while the upper limit is the power level at which the scanner consistently identifies an occupied channel with acceptable accuracy. We expect this number to be well below the -40 dBm here assumed.
- **Signal badwidth [narrow, wide]**: A narrow signal is generated by simply placing a tone at the specific channel's center frequency. A wide signal is created by placing an FM modulated carrier at the channel's center frequency with FM modulation index of 20 KHz

Because this is a characterization test, there is no need to partition the domain into equivalence classes. This analysis yields a total of 28 test cases that characterize scanner sensitivity as a function of signal level. Nonetheless, a possible partition for the signal level input could be P1 = signal level $< P_{FRS\_min}$ and P2 = signal level $\geq P_{FRS\_min}$.

b) Setup and execution: The setup for this test is shown in Figure 3. Here the signal generator is used to generate both the narrow and wide signals. The spectrum analyzer is used to measure the input to the scanner while the variable attenuator is adjusted in steps of 1dB. The scanner is then activated and the results collected (the scanner reports the channel is either empty or occupied). The same procedure is repeated 100 times for each channel for each configuration of wide and narrow signal. The result of the test is presented as the average and maximum cut-off levels.

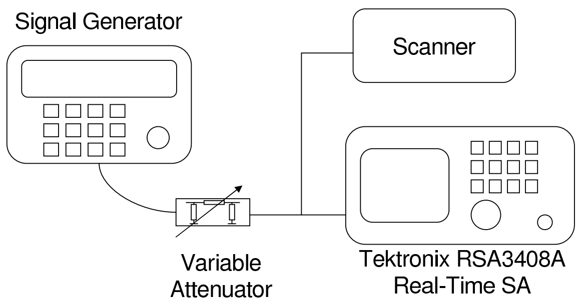

Fig. 3. Sensitivity test setup

4.1.2. Channel Occupancy Detection: The purpose of this test is to evaluate the ability of the system to reliably detect if an FRS channel is occupied or not.

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a) Inputs and domains: For this test we are defining the following logical inputs:

- **Channels [1 - 14]**
- **Signal level [empty, min, nominal]**: "Empty" means no signal, "min" is the minimum signal level required to be identified, and "nominal" is a signal level at which the system is expected to operate correctly (-40 dBm is our current estimate).
- **Adjacent channels [00, 01, 10, 11]**: This variable indicates the occupancy status of adjacent channels. The left digit represents the channel below our test channel, while the right digit represens one above it. A zero indicates the adjacent channel is empty and a one means occupied.
- **Signal duration [half scan duration, whole scan duration]**: Because the duration of a signal plays a crucial role in our ability to detect it, we test with two differen scenarios, one in which the signals are present during the whole scan period, and a second one in which the signal are only present for half that time.

The input domains, already show the equivalence classes that we have identified. For signal level the inputs can be classified in three classes: no signal, signal at the sensitivity level, and easily detectable signal. For adjacent channels there are three obvious scenarios: empty adjacent channels, one adjacent channel occupied, and both adjacent channels occupied. We decided to include the case when only one channel is occupied to differentiate between the previous and the next channel. Note that some channels only have one adjacent FRS channel. Channel 1 and 14 are the evident cases, but because channels 7 and 8 are separated by over 4 Mhz, they are not considered adjacent.

In order to avoid gaps in our test, a simplified decision table is used to identify test cases. By using this table, we can mechanically enforce completeness in our test case definition based on the values identified before. Table I shows a fragment of the table generated this way. The top part indicates test conditions while the bottom part describes the expected scanner results for the channel under test. This process yields a total of 24 test cases per channel.

TABLE I
SIMPLIFIED DECISION TABLE FOR CHANNEL OCCUPANCY DETECTION TEST CASE GENERATION (FRAGMENT)

Signal Duration	Full	Full	Full	Full	…
Adjacent channels	00	00	00	01	…
Signal level	below	min	nom	below	…
Occupied		X	X		
Empty	X			X	

b) Setup and execution: This test is perfomed using the setup depicted in Figure 4. The goal is to provide a contolled invironment in terms of channel occupation. Here, a signal generator is used to create an FM signal over a 455 MHz carrier — about 250 KHz below the first channel of the FRS band. An arbitrary waveform generator is used to generate tones that will shift the FM signal to the middle of the FRS channels. There is a pre-stored tone for each FRS channel which facilitates the creation of arbitrary environments. These tones and the FM signal are mixed together, filtered, and then amplified.

The behavior of the scanner is evaluated by recreating each scenario identified in Table I and analyzing its output. Each scenario is repeated 100 times per channel and the results are presented as the probability of correct detection, probability of false alarm (reporting an empty channel as occupied), and the probability of miss-detection (reporting an occupied channel as empty).

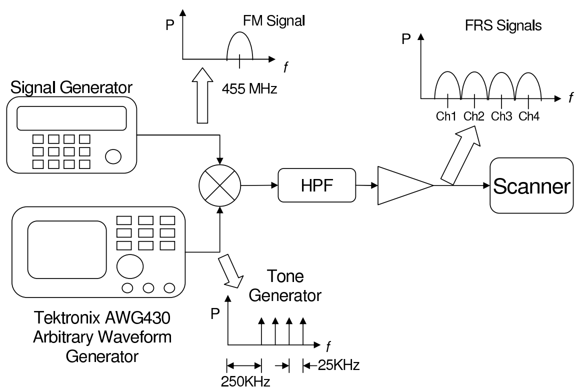

Fig. 4. Occupied channels test setup

4.2. Link establishment

The correct establishment of an ad-hoc link between the master and slave nodes, is one of the most critical aspects of the CIREN protocol. This link establishment occurs at the beginning of a transmission when a master is trying to locate a slave. It also occurs after a primary user of the FRS band reclaims the channel where a CIREN connection was initially established.

The purpose of this test is to verify the correct implementation of the protocol and report the probability of link establishment success as a function of channel properties. Due to the experimental nature of the CIREN project, its specifications are written in natural language. Therefore, the analysis performed to define the test cases provided valuable feedback identifying gaps and inconsistencies in the specification.

In order to design test cases as general and comprehensive as possible, we assume that the primary users of the FRS band can arbitrarily transmit at any time on any channel. In other words, they do not listen before talking, as would a person using a walkie-talkie. There are two stages during link establishment: rendezvous and synchonization & confirmation. Because the latter is more involved with operational modes than with DSA, the analysis to derive it's test cases is omitted.

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4.2.1. Rendezvous: In this test, we isolate the aspects that have an effect on the rendezvous process to evaluate the system's behavior. This is a system test and involves both the master and slave nodes. In order to properly execute this test, it is necessary to have control over the master's transmission channel as well as the slave's initial scanning channel.

a) Input, parameters, and domains: The complete input space for this test results in too many test cases. In order to reduce the number of test cases to a manageable number, we modify our equivalence classes. For example, we assume that all transmissions behave the same way, independently of the channel on which they occur. We eliminate redundant test cases. For example, we expect a beacon signal addressed to a different unit to always be ignored. We also fix the initial scanning point to channel 4 and then move the transmit channel across the FRS band.

The input configuration to the radios as well as the operating environment parameters identified for these tests are the following:

- **Beacon signature [UID, broadcast, other]**: This signature indentifies the intended receiver of the CIREN message. UID indicates that the beacon is addressed to the slave node under test. The slave node is supposed to attempt synchonization with beacons signed as UID and broadcast, while ignoring others.
- **Interferer [No, Yes]**: This variable indicates the presence of a primary user in the transmission channel.
- **Secondary channel available [Yes, No]**
- **Beacon power [Min, Nominal]**: The minimum beacon power is the signal level identified during the sensitivity test, while the nominal power is a value well within the range of the receiver which can be easily identified. The nominal power used in this test is -40 dBms.
- **Beacon channel [same, below, up, 8, 1]**: This variable indicates the channel where the beacon is transmitted relative to the channel where the receiver begins scanning. "Below" and "up" indicate one channel lower and one channel higher, respectively. Channels 8 and 1 are special cases because they are the first channels that would be scanned after a long jump in frequency. Channel 8 is separated from channel 7 by over 4 MHz while channel 1 is scanned after resetting from channel 14.

A fragment of the resulting decision table used to define test cases is shown in Table II. A total of 43 test cases are identified in the complete table.

b) Setup and execution: This test is executed using the generic DSA setup shown in Figure 5. The signal generator and Tektronix AWG430 coordinate the same way they did for the scanner tests in order to provide an environment with controlled channel ocupation. As mentioned before, we set the slave to always initiate the scanning process from Channel 4, while the master varies the transmission channel. It is necessary to control the availability of secondary channels for the CIREN radios. Antennas can be replaced by wires to provide a more controlled environment.

TABLE II

DECISION TABLE FOR LINK RENDEZVOUS TEST CASE GENERATION (FRAGMENT)

Beacon ID	Other	-	-	UID	UID		UID	
Interferer	-	Yes	Yes	No	No	…	No	…
Sec. Chan. Avail	-	Yes	No	-	-		-	
Beacon Power	-	-	-	nom	nom		nom	
Beacon Channel	-	-	-	same	up		8	
No Transmission	X		X					
Switch Channel		X						
Lock				X	X		X	

A successful rendezvous connection, for this test's purpose, takes place when the slave sends an ACK/NACK back. Problems with the implementation are reported and the probability of successfull link rendezvouz is calculated for 100 trials.

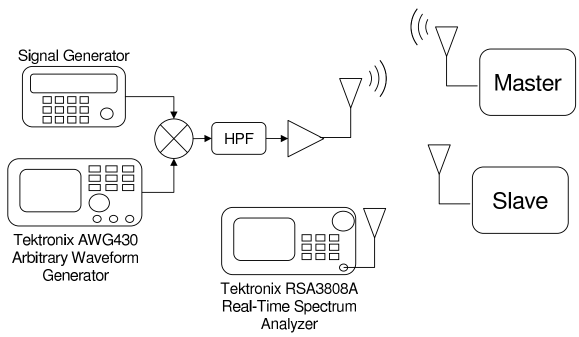

Fig. 5. Generic DSA Scenario

4.3. Link termination

Although there are many link termination scenarios to be tested, in this paper we only consider the termination of the link due to a primary FRS user occupying the transmission channel. This is the initial step towards switching the CIREN link to a secondary channel.

The purpose of this test is to verify the correctness of the system in implementing the CIREN protocol and to measure the peak and average vacancy time. The evacuation time is defined as the time elapsed between the beginning of the primary user's transmission and the CIREN transmission stopping. There are only two input variables identified for this test:

- **Interference [Rendezvous, Sync, Ack, Confirmation, Data, Reply]**: This variable indicates the stage in a CIREN transmission during which the interference occurs. For example, when this variable takes the value of Rendezvous, it means that the interference occurs during the rendezvous stage while the master node is transmitting the beacon signal.
- **Interference level [Min, Nom]**

There is no need to create a decison table for this test. The expected behavior of an interferer occupying the transmission

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channel is the stopping of all CIREN transmissions in this channel. This is independent of the signal level of the interferer, as long as it is over the sensitivity level.

c) Setup and execution: In order to measure the evacuation time, we need to be able to identify the beginning of an incumbent transmission co-located with a CIREN signal. In order to do this, we begin transmiting two FRS signals simultaneously in separate channels using a similar setup to the one shown in Figure 5. One of these signals will be sitting directly on the CIREN transmission channel, overlapping, while the other is a support signal used to trigger the measurement mechanism. A graphical representation of the signal locations is shown in Figure 6. Using this approach, we set up a spectrum mask in the Tektronix RSA 3408A Real-Time Spectrum Analyzer to measure the vacancy time. This measurement is repeated 30 times per test case and the results reported as the average and peak vacation time.

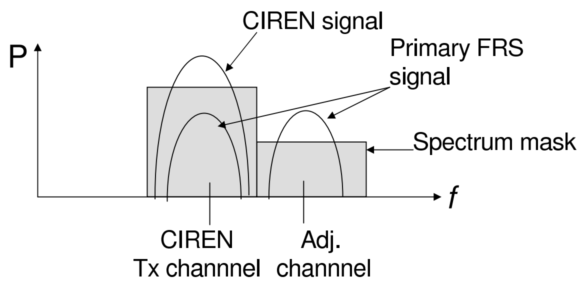

Fig. 6. Signal location for vacancy time measurement

5. CONCLUSIONS AND FUTURE WORK

In this paper, we presented the approach we followed to identify and define test cases to validate the dynamic access behavior of the CIREN radio. In this approach, independent testable features are identified and suitable test cases are developed based on boundary value analysis and decision tables on equivalent classes in the input domain of every module. A proposed setup to provide the appropriate execution environment is described for each test as well.

Because the CIREN radio is still under development, the results of the tests are not available yet. Test results will be collected and presented in a future publication once the required modules are operational. Further research is required to generalize the procedure and evaluate the adequacy of this approach and test cases to different systems.

The techniques here presented are under development and subject to further analysis and modifications. They present an initial step towards the standardization of test procedures for radios with DSA capabilities. Generalized test procedures will accelerate the acceptance and deployment of radios with DSA capabilities. Study groups like the IEEE 1900.A, are aiming at recomending test procedures for the DSA assurance of radios. This work tries to compliment these efforts by providing reference material that will spark discussion and catalize the developement of cognitive radio technology.

ACKNOWLEGMENTS

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