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Cognitive Radio Technology: Introduction and its Applications

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Abstract: The essential component for wireless communication networks is the frequency spectrum which is limited and a natural resource. Major part of this resource is sold by the regulatory bodies/governments to the service providers for mobile communications and broadcast for commercial usage. Some part of spectrum is used for military and security purposes. Remaining, like ISM bands are available free of charge for public use. As these bands are getting overcrowded day by day and at the same time sold spectrum is underutilized. These results in the need of intelligent and adaptive systems for a radio to access the spectrum called cognitive radio. In this paper we have discussed the cognitive radio and its various phases. Then various definitions to cognitive radio given by different institutions are presented. Standards which have been developed for cognitive radio and applications of cognitive radio technology have been discussed.
Keywords: Cognitive radio, cognitive radio technology, cognitive radio standards, cognitive radio applications.

I. INTRODUCTION

In wireless communication network proper utilization of radio frequency spectrum is the prime consideration. The frequency spectrum is not used efficiently due to nonflexible allocation of its license for use. These licenses are controlled by government agencies and are assigned to service providers for long duration and huge geographical area. DARPA has done measurements for signal strength distribution for frequency spectrum used for wireless communication and observed that some bands are so overcrowded that its access is a major problem and very large portion of this spectrum is underutilized. This signal strength distribution is shown in Fig. 1 for wide range of radio frequency spectrum. Only 6% of the frequency is utilized [1].

On the other hand the number of users in wireless communication network is increasing very rapidly and demand for high quality leads to spectrum scarcity [2]. A very intelligent and flexible management of spectrum is required due to this contradiction [3].

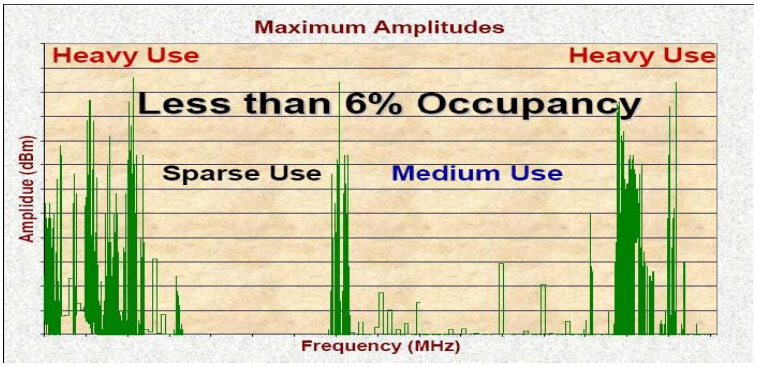


Fig. 1: Signal strength distribution of spectrum.

Spectrum utilization can be improved by adopting a policy to access the spectrum dynamically. DARPA is doing work to implement such an intelligent radio called cognitive radio (CR). CR is a new model of wireless communication, which is well thought-out as a possible way to complete the future needs.

II. COGNITIVE RADIO

As Federal Communications Commission has identified the problem of spectrum scarcity, the researchers who were working in the area of wireless communication technology have diverted their attention towards area of cognitive radio technology. With the help of advanced processors, VLSI technology, RF technology and software tools, idea of software defined radio (SDR) was given by J. Mitola in 1991. When SDR became reality and it was able to move through multiple standards, it motivated IEEE to formalize a set of rules for vertical handoffs among networks of various standards (IEEE 802.21). When a communicating device changes its wireless communication technology from one to another for transmission is called vertical handoffs [4]. Then research went on to implement such a radio that can detect and use the vacant frequency spectrum for

data transmission [5]. In addition to this if it can also remember the geographical location and time the list of vacant channels. These few ideas motivated the research and development in the field of CR [6]. So CR is a SDR which can exploit the underutilized spectrum called spectrum holes, for which the following definition has been offered: "A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user".

The inefficiency in the spectrum usage necessitates a new communication paradigm to exploit the existing wireless spectrum opportunistically [7]. Cognitive radio operation can be divided into three phases: radio-scene analysis, channel-state estimation and configuration selection. It can be considered as one of the intelligent frequency reuse scheme. For an extensive use of applications e.g. self-organizing networks, smart grid communications, public security and safety systems, CR is widely used [8]. It is similar with software defined radio in terms of re-configurability.

The main objective of CR is to provide very reliable communications needed along with the efficient utilization of frequency spectrum. The major issues in the cognitive radio are intelligence, awareness, learning, reliability, adaptivity and efficiency. This technology should use all natural resources such as time, frequency and energy efficiently. Appropriate design of antenna can make it to resonate it at multiple bands [9].

For future wireless communication network systems spectrum efficiency plays an important role as number of users are increasing very rapidly [10]. The communication network will have two types of users: primary and secondary. Primary users have purchased the license for use of spectrum. Secondary users can improve spectral efficiency by using the same spectrum when it's not been used by primary users. Secondary users should have the capability of sensing the environment. Unused frequencies can be accessed dynamically. So secondary users in wireless network needs some additional components to sense the channel and adapt accordingly. This approach of cognitive radio can be used in to satisfy the requirements of future mobile communication network by using dynamic resource management [11]. Some new capabilities like agility, flexibility, sensing and networking are embedded in cognitive radio to make it capable to use the channel

Flexibility: Cognitive Radio's flexibility is the capability to alter its configuration and type of waveform. As an example, we can operate a cell tower in cell band for telephony applications and then its waveform can be changed for telemetry applications from vending machines. For two entirely different roles the same frequency band can be used.

Agility: Ability to switch the frequency band in which cognitive radio can operate is known as agility. Basic agility is present in mobile phones, as they can function in spectrum band of 900 and 1900 Mhz. In adaptive radios the challenge is to embed this agility along with flexibility since radio can utilize different waveforms in various different frequency bands. There are however certain limitations that do exist in technology for affordability of flexibility and agility.

Sensing: The ability to study environment, more importantly the spectrum is termed as sensing. To enable adaptability, this is one of the most important components. It allows radio in cognitive radio network to be aware of the environment and also its impact on its performance. This is also required if radio needs to change its technology at different locations and time. In [13] authors have proposed an artificial neural network to optimize the sensing time for cognitive radio.

Networking: Communication between multiple radios is through networking capability. It assists in sharing the database of spectrum sensing information. This sharing of database can be extremely useful when sensing the combinations of various measurements for taking better decision about the environment. It can particularly be extremely helpful in adaptation where a group has to determine an optimum use of spectrum band resources as compared to an individual node.

Some significant definitions of cognitive radio are given as follows:

J. Mitola first introduced the term cognitive radio in his paper in 1999 and defined it as: "*A radio that employs model based reasoning to achieve a specified level of competence in radio-related domains*." [14].

In widely cited paper [15], S. Haykin defined cognitive radio in 2005 as: "*An intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier frequency, and modulation strategy) in real-time, with two primary objectives in mind: (i) highly reliable communications whenever and wherever needed, (ii) efficient utilization of the radio spectrum*." One of the main regulators FCC has defined cognitive radio as: "*A radio that can change its transmitter parameters based on interaction with the environment in which it operates*." [16].

Another primary regulator in USA, NTIA has given the following definition to cognitive radio while focusing on few of its applications: *"A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, and access secondary markets."* [17].

Finally, VT CRWG (Virginia Tech Cognitive Radio Working Group) defined cognitive radio as follows: *"An adaptive radio that is capable of the following:*
a) Awareness of its environment and its own capabilities,
b) Goal driven autonomous operation,
c) Understanding or learning how its actions impact its goal,
d) Recalling and correlating past actions, environments, and performance."

Various factors have led to advancement of cognitive radio technology. One major factor is consistent increased requirement of radio spectrum together with improvised communications and communication speeds. This has resulted in initiatives for efficient spectrum use. There are many cases where greater flexible communication is required. Along this path, there are various important milestones which have contributed immensely for development of technology for cognitive radio.

While normally a variety of different radios would be required to intercommunicate, this system would never be viable and desirable for small groups of persons, and the use of reconfigurable radios would certainly have resulted in far better communications to be achieved.

When frequency spectrum started becoming a scarce resource, the need for its efficient use was felt and several radio regulators started the work on finding the ways for its more effective use.

In 2002, A U. K Professor Cave published a report about the possibility of selling radio spectrum based upon requirement of bandwidth, leading to spectrum management as it would enable to use areas which were temporarily free and hence maximize its use in a very efficient way [18].

Similarly many other people have worked extensively on this possibility of self configuring radios. As a matter of fact the name "Cognitive Radio" was devised by J. Mitola in 2000 while writing thesis on this subject [19].

III. COGNITIVE RADIO STANDARDS

Two standards have been developed by Institute of Electrical and Electronics Engineers (IEEE) 802 community for cognitive radio, 802.11h and 802.22. In addition to this one more standard 802.11k is currently in process of development. Societies of IEEE develop and document the IEEE Standards. This is done with the process of agreement by Committee members and finally acceptance is taken from American National Standards Institute. A standard is finalized after taking views from all volunteers. The focus of these standards is to incorporate the information of radio resource management into wireless local area network (WLAN) operation.

802.22

This standard is developed for interfacing of physical layer and medium access control layer called MAC layer of point to point or point to multipoint WRAN (wireless regional area networks). These networks can be of fixed base station and terminals can be fixed or mobile operating in frequency band of '54 MHz – 862 MHz' [20].

Three types of users in wireless network: mobile radio, microwave peer to peer links, television usually coexist. Each one of them has shown underutilization of spectrum. Out of them presence of only television signals can be detected easily.

All through their history, the Ultra High Frequency bands were not allocated to service providers, as they could not estimate that implementation of new TV towers for these bands are cost-effectiveness. It was pending till the beginning of cable TV, and then it was observed that operation of small TV stations was more cost-effective.

Now technology for TV broadcasting is changing from analog to digital and it is called HDTV technology. Therefore very good quality frequency band of 108MHz for analog TV is not allocated in many countries to anyone. Keeping this in brain IEEE 802.22 WG has developed a standard to offer access to wider bandwidth in rural areas using a technique based on cognitive radio technology. The development of physical and MAC layer is in process. As MAC layer needs to manage the access to physical layer intelligently. It manages for vacating the channel whenever required. For Digital TV channels above 6MHz threshold value has been set to -116 dBm to vacate the channel. For analog TV, National Television System Committee (NTSC) has prescribed it at peak -94dBm. It has been set to -107dBm for Wireless microphone in bandwidth of 200 kHz.

Hence cognitive radios are vital for detection and classification of signals available in the environment. To keep interference level occurred in these signals to the minimum value, 802.22 standards has currently under consideration the usage of spectrum tables that can be updated by system operator as well as automatically. In those cases where the present system is not detected, to keep its impact at minimum level, traditional limits are placed for maximum transmission of power.

802.11h

802.11h has not been developed as a standard for cognitive radio, unlike IEEE 802.22. However WWRF (World Wireless Research Forum) has observed that major portion of this protocol "Dynamic Spectrum Access" has been referred as "cognitive function".

When problems started arising because of interference among devices, ITU (International Telecommunication Union) suggested rules for 802.11h standard. Here two different schemes are being used for minimizing the interference. DFS (Dynamic frequency selection) identifies the existence of any other device on the channel, and then the network is switched to another channel automatically. TPC (Transmit power control) is used for reducing the output power of each transmitter of the network to certain level that ensures interference free systems, while simultaneously maintaining an optimum performance of the network. Just to see how this protocol can be considered for a cognitive radio, the following capabilities of WLAN are required in 802.11h standard.

- *Observation:* In this standard, it is required that WLAN should estimate characteristics of channel such as link margins and the path losses.
- *Orientation*: Depending upon those observations it has to be determined by WLAN whether it is operating in a poor performing channel or along with any other device in WLAN.
- *Decision:* WLAN has to make a decision regarding changing its operating frequency or power for transmission, or both, based upon the situation.
- *Action* – Then the decision has to be implemented by WLAN.

IV. INSTITUTIONS WORKING IN COGNITIVE RADIO

For better utilization of radio spectrum frequencies which are underutilized today, cognitive radio technology can be used in various communication systems. Several Institutions like DARPA, IEEE, SDR Forum and FCC have been working on various initiatives in cognitive radio technology.

i. DARPA

In DARPA's vision of networking, cognitive radio is being seen as an important enabling technology that allows less capable nodes to perform complex operations required for making better and efficient use of spectrum and also suitable for applications which requires high data rates. Presently DARPA is working on many aspects of radio as part of next generation networks and various other ongoing initiatives. However, unfortunately the results of many such initiatives of DARPA are not presently available in public domain.

Program manager of DARPA, Preston Marshall has however promised that in near future, various organizations will need to reveal results online. It has developed a sensor which is capable of processing 5 GHz frequency that can detect sub noise floor signal (below 20dB) by using cyclostationary features and Rockwell has been assigned for miniaturization of size of this sensor.

The XG is a project for development of technology which DARPA is sponsoring with defined goals to "Develop both the enabling technologies and system concepts to dynamically redistribute allocated spectrum along with novel waveforms in order to provide dramatic improvements in assured military communications in support of a full range of worldwide deployments."

In 2003, DARPA's Preston Marshall said, "The primary product of the XG program is not a new radio, but a set of advanced technologies for dynamic spectrum access."

ii. IEEE

The IEEE has given major attention towards cognitive radio. IEEE have proposed definition and submitted it to the FCC. The issues of cognitive radio were studied by IEEE 1900 group. Three subgroups (1900.1, 1900.2, 1900.3) under this group focused on terminology, definitions, testing process, verification process, software tools and certification for regulators for cognitive radio [21].

First conference on "Dynamic Spectrum Access Networks" was held in November, 2005 by 'The IEEE Communications Society'. The main focus of this conference was on technologies required for implementation of cognitive radio, networking, spectrum sensing, study of communications, regulations, to assess its suitability for implementing cognitive radio networks. Some standards have been developed by IEEE 802 group as already discussed in Section 3.

In October 2004, while responding to a notice for proposed rulemaking (NPRM), issued by FCC, a working group IEEE 802.22 on WRAN was formed [20]. This was given the task of defining standard for air interface which was based upon CR sensing (in the frequency spectrum allocated for Television Service) for regional area wireless networks for efficient working of unlicensed devices.

iii. SDR Forum

Two groups: "The Cognitive Radio Special Interest Group" (CRSIG) and "The Cognitive Radio Working Group" (CRWG) were formed by SDR Forum to investigate the issues of cognitive radio. The former

on is given the responsibility to explore smart profitable uses of cognitive radio. The second one is to formulate the cognitive radio definition and explore the technologies required for it. The SDR Forum conducts technical conference yearly where importance is given to the issues of cognitive radio.

iv. FCC

The FCC organized a workshop to study the impact of cognitive radio technology on spectrum utilization and issues which can raise with its implementation in 2003. After this workshop FCC concluded a definition for cognitive radio given in section 2. FCC also took interest in formulating the regulations for the deployment of cognitive radio technology in unlicensed frequency bands. It was also explored that this new technology can also be extended to UHF and ISM bands. Then FCC took steps to expand it to unlicensed 5 GHz band. FCC also proposed the requirement of the devices which can operate in these bands and with capability to access spectrum dynamically along with characteristics of transmission power control.

Many other institutions like BWRC, Virginia Tech, E^2R and Winlab are also doing research in the field of cognitive radio.

V. APPLICATIONS

The capability of adjustment according to surrounding has made CR popular in communication world. CR provides number of benefits in various field like military, public, government, commercial and safety. In the following section frequent applications of cognitive radio are discussed:

a) Efficient spectrum utilization.
b) Increasing link reliability.
c) Low budget radios
d) Increasing SDR techniques
e) Automated radio resource management

(a) Efficient Spectrum Utilization

Efficient utilization of spectrum can be done by CR as shown in Fig. 2. [22]. There is lot of improvement in various fields by effective spectrum utilization as given below.

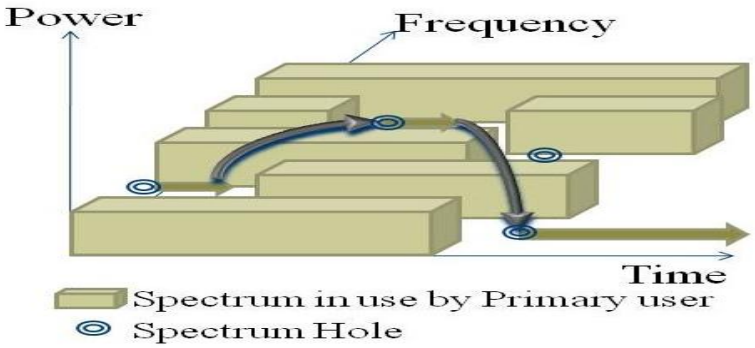


Fig. 2: Efficient utilization of spectrum

(i) Military

With the kind of spectrum flexibility and agility that CRs have, it has become an extremely essential and useful technology. Its ability to interoperate in various different radio frequency standards along with its capability of sensing interferer's presence has led to its wide spread usages. Acknowledging these properties and benefits of CRs, military has started using this important technology for its use. The military community obviously is more interested in secret and secured communications. Since CR is always aware about its surrounding environment and has the ability to identify any communication paraphernalia that belongs to enemy, it has started being used extensively and has adopted a very big role in the communication equipment being used by the militaries. The capability of these intelligent radios to transmit data in uninterrupted, secure and secret style has led to its widespread use in military applications. Defense Department of USA has recently started devoting great efforts for development of CR technologies for intelligent communication and has started new initiatives such as XG (next Generation) project.

(ii) Public Safety

CR is playing very important role in public safety and emergency. Public safety agencies are in immediate need of an additional spectrum at the time of any emergency situation. CR can provide an alternative spectrum at the time of congestion. This concept is basically based on the sharing of radio spectrum that can

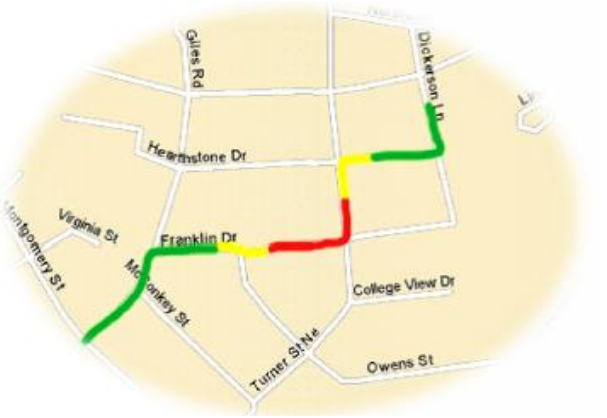
help in deciding call main concern and their reaction time. The jurisdiction can take help of cognitive radio in operating the others communication equipment and fetching their information in case of suspicion. CRs can provide a channel between two stations even if they are using two different radio systems. This approach can help in secrecy. Cognitive radio technology due to its capabilities has attracted the attention of Justice Department of USA and accordingly it has employed the NPSTC (National Public Safety Telecommunications Council) to focus on research in CR.

(iii) Broader Impacts and Commercial Use

Spectrum sharing is a very important part of dynamic spectrum allocation (DSA). We know that biggest challenges in implementation of CR network are policies and regulations authorities. Possible availability of radio spectrum along with prediction accuracy is also a cause of concern. The use of CR technologies has converted conventional approach of static assignment of frequency into dynamic spectrum frequency assignment. With ever increasing demand of mobile devices and more demand of spectrum, it is becoming difficult to satisfy this demand. Detection of presence of any device and identification of any interference because of this is very important input information needed for intelligent sharing of spectrum through its dynamic allocation and reconfiguration of radio. When devices are given access to wider frequency spectrum, this problem becomes more complicated. Mainly the problem of interference has increased due to successful addition of wireless local area network into the ISM band. Although some technologies like dynamic frequency selection and adaptive modulation are there, which help us to counter this problem, but by including cognitive radio, we not only can counter the problem of interference in ISM band but also can improve the condition of current system. We can also produce some positive results in spectrum allocation by using simple algorithms.

(b) Increasing Link Reliability

After improved and efficient usage of radio spectrum, another very important application of this technology is enhancing the link reliability. Adaptive radios enhance the link reliability through dynamically adapting transmission power, modulations, and error correction techniques [23]. As we are aware that a CR can learn, remember and adapt the environment of its surroundings, so the situation can be improved to a large extent. We can understand by following simple example.



[Signal quality: Green-Good, Yellow-Transitional, Red-Poor]

Fig. 3: Signal quality and path followed by a mobile user

Fig. 3 showing a path that a mobile user follows daily, red sign showing poor quality of signal if user is cognitive radio enabled then user by its geo-location and learning quality from the environment it can modify the signal characteristics at geographical basis so that user can come out from this problem of coverage gap.

(c) Less Expensive Radios

When we add complex circuitry in any radio it happens to be expensive, addition of cognitive principle we can reduce the cost of device. The reason behind reduction in cost is implementation of most of the feature of CR at lower cost and with less complexity. Another fact behind reduction in cost is the base of implementation of CR that is SDR. This enabled the CR to improve in performance with low cost as compare to analog components. Addition of two hundred software cycles per second is almost costless whereas improvement of performance by 3 dB of a RF front end can be a quite costly affair. As we have seen earlier opportunistic channel utilization improves the capacity of spectrum. CR not only improves the channel capacity but also it dedicates some of its components for including the components of signals which are outside from the limit of channel. Such analog components for low performance transmitter can be incorporated in the CR. This

low cost radio does not degrade the signal quality due to lack of bandwidth because it uses opportunistic devices which is capable of finding the spectrum holes.

(d) SDR Techniques Enhanced by CR

Several technologies that are based on the SDR can be improved by the technology of CR. These various technologies are spectrum trading, antenna array algorithms and interoperability. The main advantage of SDR is smart antenna technology but performance of system can be greatly improved by adding some features that enables th e system to learn and to adapt the environment.

For network shown in Fig. 4, two links are present - one is there between green nodes and other is there between white nodes. When the node at bottom left opts for implementing transmission through beam forming, one can anticipate a large gain in performance of green nodes. But this is not desirable as white nodes will also experience large interference. If green nodes are aware that any white node is also operating in the same potential beam then green nodes could have adopted the same path not impacting white nodes by using multiplexing in frequency and time domain.

Software radios feature frequency agility enables user for spectrum trading. In trading of spectrum, various owners sell or buy spectrum to or from service providers as per demand prevalent in the market. Basically software radio is technology that can help user in spectrum trading business. With the help of SDR users nodes instructed to change their characteristics according to environment. But it is available up to service providers only, they follow a fix procedure that take a weak or more then this in changing characteristics of node imagine if this facility can be provided to every user, means user can choose its own bandwidth according to its needs.

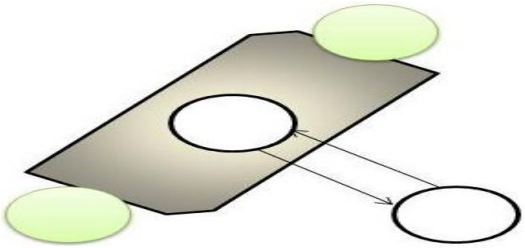


Fig. 4: Ad-hoc beam forming with negative effects on network performance

The CR user is conscious about the environment and spectrum availability and this leads to his ability to negotiate for required bandwidth with the service providers. This transaction of spectrum can be for short period time and may be in milliseconds. Simultaneously service provider's transaction speed of base station will also be enhanced. This will allow service providers to shift resources as per market dynamics leading to reduction in blocked or dropped calls.

(e) Automated Radio Resource Management

Establishment of wireless network is followed by tuning of radio parameters to get maximum output from network. The main parameters are allocation of channel between sectors, antenna patterns, call drop thresholds, timers, level of power and others all adjusted to get efficient output. As number of wireless network is increasing and centralize service providers moving to cater the office and home segment, need for efficient use of wireless network has increased. As CR is capable of learning and adopting, it can play a very important role in distribution of network and in automatically updating the radio parameters in efficient direction.

VI. CONCLUSION

The capability of adjustment according to surrounding has made cognitive radio popular in communication world. Introduction of cognitive radio will improve the spectrum efficiency. Various definitions have been given to cognitive radio by institutions. Many Standards have been developed for cognitive radio technology. Many institutions are working in this field very actively and proposing new technology for its implementation. Cognitive radio technology has many applications in the field of military, public, government, commercial, and safety.

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