Cooperative Awareness in Cognitive Wireless Networks for Jamming Control

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***Abstract*—In cognitive wireless networks, opportunistic network devices can be programmed to take advantage of licence holders' idle times and dynamically adjust their operating parameters to improve transmissions. For this to be successful, these idle periods must be reliably detected. To support this requirement, this work proposes a cooperative detection mechanism for the signals transmitted by the licenced system through the use of positioning-enabled devices. Such devices can provide information to guide and control opportunistic network devices to limit interference to the licenced system. Simulations show that keeping interference within specification limits makes it possible to maintain opportunistic network communications in an ad hoc scenario with quality.**

***Index Terms*—Wireless Networks, Cognitive Wireless Devices, Ad Hoc Networks, Jamming Control, Automatic Power Control.**

I. Introduction

Despite all the flexibility offered by cognitive wireless networks [1], whether cognitive wireless devices forming part of an opportunistic (or secondary) network can operate without unduly interfering with licenced (or primary) communication systems is not straightforward. This understanding is essential for spectrum regulation and for allowing secondary systems to share bands with primary systems. In the US, the analogue TV band is subject to regulation by the FCC, which has been issuing new usage rules since 2008 [3]. Moreover, there is no consensus on ensuring that different cognitive wireless networks sharing the same spectrum can operate properly without interfering with each other or other networks and systems.

The problem of interference between primary and secondary devices has received much attention from the beginning [6], [7], [8], [18], [19], [20]. All used theoretical and probabilistic analysis based on a primary network model comprising a transmitter and multiple passive receivers.

As a slight variation of this network model, we proposed a secondary network of fixed and mobile nodes composed of cognitive wireless devices that collaboratively detect the transmissions of the primary network and use this information to adjust their transmission power, maintaining connectivity between the nodes without harming the primary nodes. Here, connectivity is generally understood as a simple quality measure.

Following this introduction, Section II provides an overview of the basic concepts needed to understand the work, together with describing the components of primary and secondary networks. The next section quantifies the parameters, describes the scenarios, and presents simulation results. Finally, Section IV concludes the paper and outlines future work.

II. Description and System Concepts

The proposed system comprises a secondary *ad hoc* network with FIXED and MOBILE nodes consisting of cognitive wireless devices that allow cooperative detection of primary network transmissions. This information is used to adjust its transmission power. The connectivity between each secondary node is maintained, and the interference detected by the primary network is dynamically controlled.

The primary network has a licence and uses the frequency band (the band of interest). The secondary network operates opportunistically and avoids exceeding the interference limits that are set (and communicated) by the primary network.

In both networks, all nodes are transceivers that do not use spread spectrum techniques, always exchange data within the same frequency band (interest band), and use a medium reservation mechanism similar to RTS/CTS in IEEE 802.11 to reduce the hidden terminal problem and to inform other nodes within range of the ongoing communication.

No control channel is established. Instead, distributed control is used on the secondary network via message exchange. The networks are described as follows.

Primary Network. Primary network nodes (**P**) can only communicate with each other. They have a fixed transmission range (standard range) which is used as a reference for other nodes. During transmission, **P** nodes can be detected by secondary network **S** nodes.

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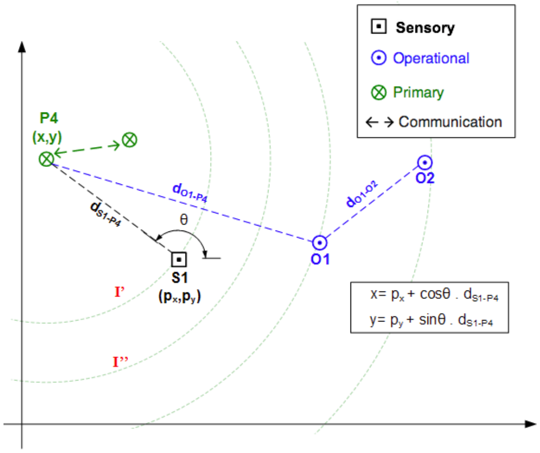

and

Fig. 1: Interference circles and primary node (**P**) positioning mechanism.

The jamming limit (I) is set by the **P** nodes and communicated to the secondary network. The value, by default, is related to the node's location. However, it could be calculated for a different location, taking into account the existence of *allowable interference level circles* that increase with distance (Figure 1).

Secondary network. It uses cognitive wireless devices and consists of nodes with direct operational and sensing capabilities. These nodes are responsible for network communication and sensing. They can collaborate to detect primary node transmissions and calculate signal direction and range. The *sensor nodes* (**S**) perform the sensing function, and the *operational nodes* (**O**) carry out an operational data exchange function.

To reduce problems caused by multipath and shadow effects [12] and to improve the accuracy of primary node detection, we have *implemented* cooperative sensing for all **S** nodes.

The ability of secondary network nodes to estimate their position is critical to network operation. When choosing a positioning system, the main requirements are accuracy, reliability, scalability, and energy efficiency. Although not implemented, we have *assumed* that all secondary network devices have a positioning system.

Most of the time, **S** nodes are in *passive mode* (they do not transmit), and they remain committed to reading the transmissions of **P** nodes and estimating their location. Two mechanisms do this:

- *Transmission detection mechanism*. Various scientific applications have been found for signal detection mechanisms, including communications. [17] shows a collection of techniques and results using signal detection techniques developed in recent decades. Since then, several methods have been proposed for energy detection [15], signal waveform detection [4], signal ciclostationarity detection [15], matched filter detection [2], and more. Each has its pros and cons, depending on the signal characteristics it detects. For simplicity, we have assumed that **S** nodes in the range can detect the transmissions from other nodes using energy detection.

If the **S** node determines that a detected signal is not from a secondary network node, it will alert all **O** nodes within the range that a **P** node transmitter is present. It will then begin calculating the P node estimated position using a positioning mechanism. And then, it sends another message to the **O** nodes with the estimated position of the transmitting **P** node. This **S** node then resumes passive operation until another transmission is detected.

- *Primary positioning mechanism*. This mechanism is initiated after it detects the transmitting node and fails to identify it as a secondary node.

Several approaches have been made to correctly determine the distance between two network nodes, including the Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA), and Received Signal Strength (RSS) [5], [14]. In such systems, the main sources of error are the non-line of sight (NLOS) equipment and the uncertainty in the measurement itself. Methods for detecting and correcting errors due to NLOS are presented in [11], [9].

In general, errors in distance measurements vary with time or are static but vary with the environment. By taking multiple measurements within a time window and averaging them, the time-varying errors caused by additive noise and interference can be reduced. The static errors, which are dependent on the environment, are mainly the result of the obstacle layout in the working area. If the working area is irregular, this type of error is considered unexpected and can be modelled as a random variable.

For this article, we have *assumed* that the **S** node uses the AoA method to obtain a location line where the **P** node's transmitter is positioned. The RSS method was also used to obtain distance estimates for the same **P** node.

The (x,y) position of the detected **P** node has been obtained according to Figure 1 and communicated by a message sent to **O** nodes within range. The accuracy of estimating the position of the transmitting node and its distance depends only on the number of **S** nodes performing the detection. In the case of simultaneous transmissions detected by the same **S** node (multiple transmitting nodes)[1], the location window is extended.

The **O** nodes can communicate with each other (point-to-point) and also share a frequency band with **P** nodes, provided it's not being used by them, in order not to exceed interference limits, I. In return, they receive information from the **S** nodes to control their transmission power. Its transmission range is adjustable between zero, corresponding to no transmission, and the default range, corresponding to maximum transmission power.

When the estimated position of the transmitting **P** node is obtained by the **S** nodes in range, the adjustment of the transmission power of the **O** node is enabled by the information received from the **S** nodes that promoted the detection and location.

[1]The different detection of simultaneous transmissions is related to the spatial separation of the detected signals by a directional antenna used in the detection.

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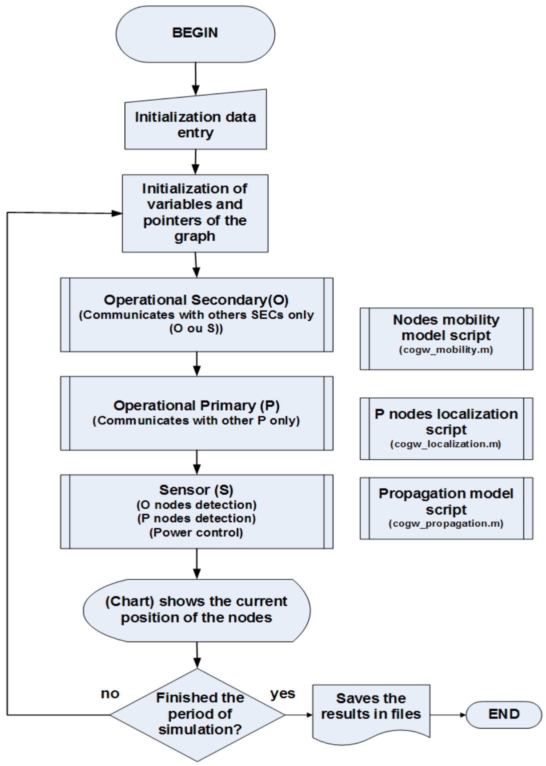

Fig. 2: Simulator flow chart built using Matlab.

To validate the proposed system, we have made the following *assumptions* regarding how the networks work:

- All messages exchanged over the secondary network include the identification of the node's origin, destination, position, and transmission power;
- All **S** nodes have a receiver sensitivity of 10 dB above the noise floor in the frequency band of interest;
- All **S** nodes have a pair of antennas: one for communication and another (directional antenna array) to detect primary transmissions (AoA);
- In the operational area of the network, there are no other RF emissions capable of introducing significant errors in the proposed mechanisms;
- All communication is by error-free message exchange. However, we do not consider throughput or the use of routing protocols at this evaluation stage.

III. Simulation: Description and Results

To evaluate the behaviour of the cognitive network, we built a simulator using Matlab [10]. This simulator was divided into blocks, as shown in the flowchart (Figure 2).

To evaluate the behaviour of our networks, we have created 4 scenarios: 3 FIXED and 1 MOBILE.

In the **FIXED scenarios**, we first distributed the **S** nodes over the area and then the other nodes. All were positioned so that the signals transmitted by both the **P** and the **O** nodes could reach the **S** nodes. The position of the nodes in both networks was important. The main requirement was that the primary and secondary networks did not completely overlap and caused transmission failures in the secondary network while trying to maintain interference limits. The **P** nodes were always within range of each other (Figure 3), as were the initial **O** nodes. The scenarios were summarised in Table I.

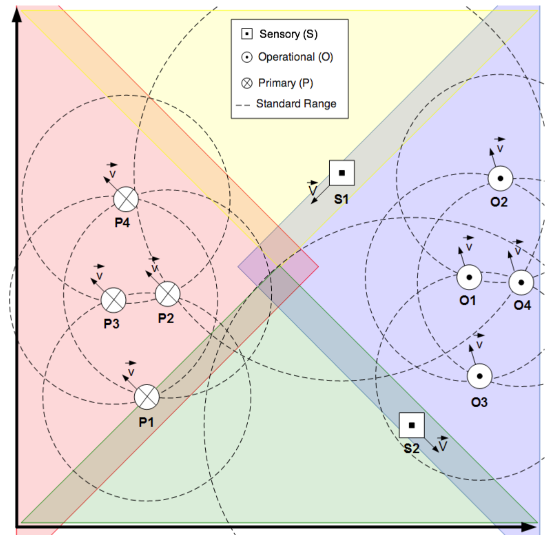

Fig. 3: Positioning and mobility schemes for FIXED and MOBILE scenarios.

TABLE I: Evaluated scenarios.

Scenarios	Nodes		
	Operational	Primary	Sensor
#1	O1 and O2	P1 and P2	S1 and S2
#2	O1 to O4	P1 and P2	S1 and S2
#3	O1 to O4	P1 to P2	S1 and S2

The initial transmission power of the **O** nodes was between 80% and 100% of the power required to achieve the standard range. Communicating **P** nodes used maximum transmission power within their normal ranges.

The signal is received at the location of the **S** node as *pr*, already attenuated according to the *log-normal shadowing* propagation model [13]. So, in the **S** nodes, we have to guarantee that ($\sum pr_O \leq I'$) (Figure 1) does not cause interference beyond what is allowed by the **P** nodes.

According to Figure 3, node **S1** initially makes the detection before **S2** and detects first **O1** (and **O3**) and later **P1** (and **P3**). In this case, it should be noted that the reservation mechanism of the **O** nodes prevents the simultaneous transmission of others **O** nodes. Depending on the scenario, node **S1** will perform the following calculations, where the variable η represents the noise floor:

$$SINR_{O1} \approx \frac{pr_{O1}}{\eta} \ , \ SINR_{O3} \approx \frac{pr_{O3}}{\eta}$$

(Without interference among the P nodes)

$$SINR_{P1} \approx \frac{pr_{P1}}{pr_{O1|O3} + \ \eta} \ , \ SINR_{P3} \approx \frac{pr_{P3}}{pr_{O1|O3} + \ \eta}$$

In the event of a packet collision in receiver **S1** (due to simultaneous transmissions or RTS/CTS packets), measure-

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ments are rejected, and **S1** waits to receive discrete signals instead.

In the **MOBILE scenario (4)**, consisting of 4 operational nodes (**O1** to **O4**), 4 primary nodes (**P1** to **P4**) and 2 sensor nodes (**S1** and **S2**), the available area was divided into 4 sections bounded by the diagonals of a square. The **P** and **O** nodes were positioned in opposite sections, with a small overlap near the centre of the square (Figure 3), following the group mobility model based on *Reference Point Group Mobility (RPGM)* within the respective sections.

The movement of the **S** nodes followed the *Fixed Waypoint (FWP)* mobility model. The movement was performed in opposite directions along two semi-diagonals of the square bounding the **O** nodes. The mobility models are described in [16].

In this scenario, **S1** and **S2** can detect the transmissions of nodes **O1** to **O4** and nodes **P1** to **P4**, but not consistently as a result of the movement described above. The initial power transmission value of the nodes has been chosen in the same way as in the FIXED scenarios.

The signal received at the **S** node position is *pr* and already attenuated according to the propagation model. However, in the **S** node, we have to guarantee that ($\sum pr_O \leq I'$) at a given time (snapshot).

As in the FIXED scenarios, the problem is approached so that if there is a packet collision at the **S1** receiver, the measurement is discarded, and a new detection is awaited. As the speed of the node is low, for the calculations, we have assumed that the reserved medium circle is centred on the nodes [2].

S node measurements are identical to the FIXED scenarios. Still, the increased mobility introduces complications, mainly for the primary location mechanism that needs to establish a position line in a short time interval (location window $\leq$ snapshot). Much of the problem is therefore related to the positioning algorithm.

For the simulation, we used an obstacle-free square area with side D to position the nodes for each scenario. The variables used, and their values are summarised in Table II.

TABLE II: Used variables.

Name	Value	Obs.
D	100m-3000m	square area side
f	1GHz	utilised frequency
η	-100.9 dBm	*noise floor*
X	$N(0;5^2)$	log distance path loss
Y	$N(0.01d;0.05d^2)$	range error (RSS)
ϵ	1%	positioning error
ϕ	1%	AoA error

For the calculation, we have *assumed* that the transmission medium is the atmosphere, at sea level, with a unit refractive index, and that the propagation speed of RF waves is the same as that of light in a vacuum. Transmission power (EIRP) is 0 dBm, corresponding to the standard range.

[2]However, as the nodes are in motion, the reserved circle cannot assume a circular shape centred on the sensors themselves. It can take any shape.

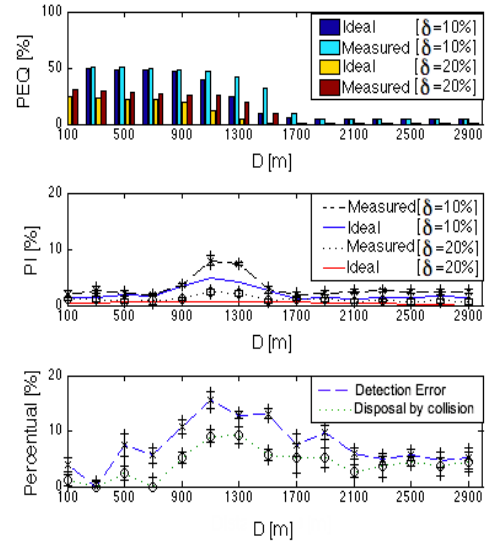

Fig. 4: Scenario 1.

We represented the shadowing effects as a normal random variable $X \sim N(\mu, \sigma^2)$ (log-normal shadowing propagation model). The maximum exchange time of messages (RTT) is on the order of hundreds of μseconds for the largest distances between the nodes.

Concerning the location of **P** node transceivers, we considered only one error in estimated distance d, which considers the variable and static errors dependent on the scenario. Which has been modelled as a normal random variable $Y \sim N(\mu, \sigma^2)$ [14]. The AoA determination error (ϕ) and the error due to the positioning system (ϵ) are both fixed.

In the MOBILE scenario, the nodes have a maximum speed of 1.8 m/s, equivalent to a normal walk. With this in mind, the displacement of nodes during the message exchange time plus the time spent by the positioning mechanism to obtain a **P** node estimated position maximum of 6.5 m.

We considered interference at the **P** node when the interference level I is exceeded. As an adjustment method for the power control mechanism, we used 10% and 20% values for the adjustment factor δ [3] in the calculation of I (interference limit projected onto the sensor node position).

For the value of I, we used -90 dBm, similar to the detection limit of commercial carrier interfaces following the IEEE 802.11b standard. The value of I refers to the (fixed) limit of interference tolerated by **P** nodes, which is released at the beginning of the operation of the primary network.

Our goal is to show that because the licenced network itself communicates the allowable interference limit through its transceiver position, a secondary network can operate without

[3]The use of an adjustment factor aims to minimise the effects of errors in the detection of transmissions from **P** nodes, as well as the collision effects in **S** nodes between packets from operational and primary nodes that can be observed for scenario 1 (Figure 4). These errors are non-deterministic because their causes are also non-deterministic.

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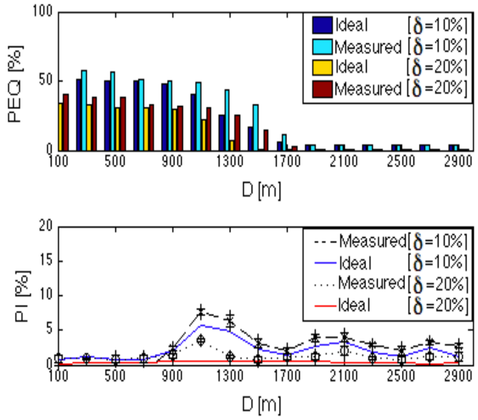

Fig. 5: Scenario 2.

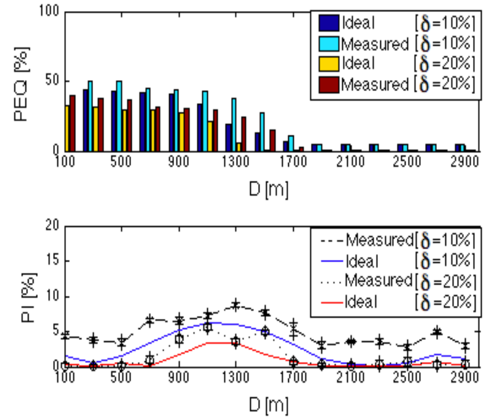

Fig. 6: Scenario 3.

interfering with the licenced network. Therefore, while observing the communication between **O** nodes, we individually evaluated the *interference percentage (PI)* greater than I, over the P node, in each scenario.

By evaluating the connectivity of our **O** nodes, we also show that the quality of communication in the secondary network can be maintained despite limiting the interference generated. In this case, we evaluate the *percentage of broken links (PEQ)* in the secondary network through the power control performed by the **O** node.

For comparison, we created a *external network unit* that acted as a *reference*, providing ideal, error-free measurements for the position, location, and transmission power of the **P** node. This unit provided *ideal* values for PI and PEQ.

To observe the behaviour of the nodes, we varied the available square area by changing the value of D, which corresponds to the square's side length. For the simulation, we varied D from 100 m to 3000 m using a 100 m scale, and for each scenario, we ran 30 simulation rounds for each value of D for a total of 900 rounds.

The traffic on the primary network was modelled as an ON/OFF exponential source, with ON and OFF period averages of 700 ms and 300 ms, respectively. Data was generated at a rate of 64 kbps during the ON period. With this information, we began to analyse the results.

For $\delta = 10\%$, in the FIXED scenario 1 (Figure 4), it is interesting to note that the *measured value PI* is always greater than zero at the **P** node, but for D of 100m-800m and for D between 1600m-3000m the value of PI is lower, less than 4%.

For values of D between 800 m and 1600 m, the value of PI has a maximum value of 9%. Analyzing the causes of this increase, we see that the **S** nodes have a high number of message collisions sent simultaneously by **O** and **P** nodes in the same intervals of D values. During such message collisions, we observe that the **S** nodes discard the measurements, causing PI to increase.

Another factor contributing to interference is the window of time required for the positioning mechanism to obtain the estimated **P** node position. During this time, **O** nodes continue to transmit and cause interference. In addition, the signal from the **P** node fades as the distance from the **S** nodes increases, resulting in poor detection.

Behaviour similar to the FIXED scenario 1 can be observed in other FIXED scenarios (Figures 5, 6 e 7) and can be attributed to the explanation given above.

In the MOBILE scenario (Figure 7), we have observed that an increase in PI does not occur as in the FIXED scenarios due to the variation in node position.

The low speed of the nodes, together with the restriction of their movement to defined areas and with the little intersection between them, produces a value of PI that remains lower than 10% throughout the simulation.

About the *value of PEQ* measured in the secondary network (Figures 4, 5, 6 e 7), we see that in all scenarios the PEQ values are high for small values of D and decrease as D increases.

This behaviour is due to the small distances between the nodes and several periods of silence in the **P** nodes, which make it necessary to control the transmission power in the secondary nodes, as they can cause high values of PEQ. Even under such unfavourable conditions, it is possible to maintain the connectivity of the links (100%-PEQ) to within about 40% to 50%, depending on the scenario.

Up to a certain value of D, due to the propagation effects, the signals have less range, and therefore, the power control is activated less frequently, resulting in a more pronounced drop in the PEQ curve.

Increasing δ to 20% and looking first at the FIXED scenarios, we have noticed that the measured PI is close to zero, assuming values up to 6% for the values of D between 800 m and 1600 m, where the incidence of detection and collision errors is high. The value of the measured PEQ also shows a reduction; consequently, the links' connectivity (100%-PEQ) increases from 60% to 70%, depending on the scenario. In the MOBILE scenario, we observe that the measured PI remains below 7% for the whole range of values of D, and the

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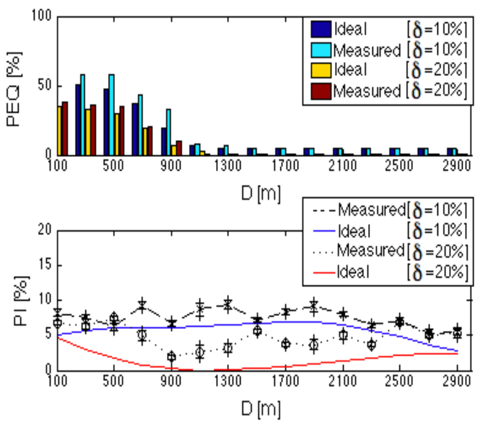

Fig. 7: Scenario 4.

measured connectivity is 60%.

IV. Concluding remarks

Given the goal of network and service convergence, the need for spectrum reuse, and the increasing ubiquity and penetration of broadband access, among other factors, we conclude that it is only a matter of time before we see large numbers of secondary networks in operation.

Varying the model of a primary network where there is a transmitter with several passive receivers, our results, with two *ad hoc* networks and FIXED and MOBILE nodes, show that we can implement a (simple) interference control on primary nodes with only a mechanism of individual positioning and a signal source detection system (goniometer). At the same time, an acceptable level of connectivity is maintained between the secondary network nodes as a simple indicator of communication quality.

Future work will focus on adapting the positioning mechanism to be more effective, implementing a collision reduction mechanism, and establishing other metrics and more “dense” scenarios for evaluation.

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