Performance Analysis of WSN Deployments for Monitoring Structural Health of Buildings to Prevent Disasters in Ecuador

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Abstract– Every important infrastructure should have a way to prevent disasters by the analysis of critical data taken from strategically placed sensors; due to its low cost and availability, wireless sensor networks (WSN) are suitable for applications involving structural safety of buildings and the development of a first alert disaster prevention system. With the recognition of the importance of structural safety, structure health monitoring (SHM) is now considered an important research topic in engineering. Unfortunately recent earthquakes in Ecuador have caused hundreds of casualties and infrastructure damages, even in cities like Guayaquil faraway from earthquake epicenters. This catastrophic situation alerted about several weaknesses that could be strengthen with new technological solutions like the deployment of WSN for structural health monitoring and disaster prevention. In this paper, a typical tall downtown building was selected and the design of a WSN that could be used for disaster preventions was proposed and their performance analysis was presented based on channel capacity under different noise backgrounds [1]. From here, an early warning system for natural disasters could be easily implemented to reliably diagnose the structure health of the mentioned building. In summary the major contribution of this work is to reinforce the need of having some kind of disaster protection for building infrastructures and provide through the analysis of the channel network capacity of a downtown building in Guayaquil, a first step toward the implementation of an early warning system for natural disasters that could save many lives, employing the cloud and available wireless technologies.

Keywords-- wireless sensor networks; channel capacity; structural health monitoring.

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Abstract*– Every important infrastructure should have a way to prevent disasters by the analysis of critical data taken from strategically placed sensors; due to its low cost and availability, wireless sensor networks (WSN) are suitable for applications involving structural safety of buildings and the development of a first alert disaster prevention system. With the recognition of the importance of structural safety, structure health monitoring (SHM) is now considered an important research topic in engineering. Unfortunately recent earthquakes in Ecuador have caused hundreds of casualties and infrastructure damages, even in cities like Guayaquil faraway from earthquake epicenters. This catastrophic situation alerted about several weaknesses that could be strengthen with new technological solutions like the deployment of WSN for structural health monitoring and disaster prevention. In this paper, a typical tall downtown building was selected and the design of a WSN that could be used for disaster preventions was proposed and their performance analysis was presented based on channel capacity under different noise backgrounds [1]. From here, an early warning system for natural disasters could be easily implemented to reliably diagnose the structure health of the mentioned building. In summary the major contribution of this work is to reinforce the need of having some kind of disaster protection for building infrastructures and provide through the analysis of the channel network capacity of a downtown building in Guayaquil, a first step toward the implementation of an early warning system for natural disasters that could save many lives, employing the cloud and available wireless technologies.

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I. Introduction

Ecuador was hit by a powerful earthquake in April of this year, the worst tragedy in the last 60 years at least 673 people were killed [2], many building including hospitals and schools felt down, with devastating consequences in the cities of Portoviejo, Manta and Muisne; after the earthquake, the big problem that comes to light is the damage that occurred in different infrastructures, 243 building in Guayaquil registered partial damages, including bridges and some infrastructures with irreversible consequences [3]; this situation could have been mitigated by adopting preventive measures like: adequate political decisions (i.e. reinforce inspections during building time) or by the use of technological tools.

Adequate political decisions is the responsibility of Community authorities, but at earthquake time, many things were not right. By the seventies Ecuador began adopting building codes but they were not strictly followed and construction quality was quite poor. Low standards of care made buildings vulnerable and dangerous.

The use of technological tools, is a solution achievable by the application of WSN as part of a disaster prevention management scheme to provide through the analysis of data from sensors, an early alert system that could save many lives [4]. In this respect WSN, have undergone significant technological developments and offer great flexibility, tiny size and do not require any wires.

A WSN consist of spatially distributed autonomous sensors nodes that monitor physical or environmental conditions and cooperatively pass their data to a special sensor node called gateway which connects the network to a main location for further data analysis [5]. With recent advances in electronics and wireless communications, it is possible to manufacture tiny sensor nodes, characterized by its low power consumption, small size and low cost. Wireless sensors are a significant improvement over traditionally wire sensors and could be an integral part not only of building structures but of a multiplicity growing number of applications.

To protect the structure of buildings, it is not enough to simply count with security cameras to show the position and movements of people and things; a great complement to this, is to have a WSN to monitor the structural health of the building, before, during and after a natural disaster such as an earthquake; with a network that could show the state of critical parameters subject to constant monitoring that could allow prevention timings of critical importance [6].

The growing wave of natural disasters has revealed the great deficiency of anti-seismic structures in the country, so this study can bring great benefits to buildings that managed to escape unharmed after the April earthquake, due to the fact that after this disaster, the Ecuadorian Government has develop several initiatives to have a better control of constructions in the country; even though they count with enough regulations they are not properly enforced. Normally construction revisions were not taken with sufficient depth.

In many countries worldwide, there already exists anti-seismic technologies capable of damping in some way the

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destructive force of telluric movements, some of them are mentioned below.

In Mexico, the Autonomous University of New Mexico (UNAM) has implemented sensor network systems for the monitoring of some of its buildings. The system that they applied consists of 5 sensors, which give information about the intensity of an earthquake and the state of the structure after it. These sensors work based on references established for the structure and the records they have about events that occurred previously. In this way the system shows alerts and generates preliminary reports about the structure [7].

In places like California in the United States, they already exists early warning systems for earthquakes like the CISN (California Integrated Seismic Network). This network is made up of sensors that, when they detect the waves caused by the earthquake, emit alert signals to a base station, which transmits the message to the zones that will be impacted by these waves, currently it is possible to gain up to 10 seconds of advantage [8].

Another clear example is the system developed in Japan by the Japan Meteorological Agency (JMA), known as EEW (Early Earthquake Warning), this is an earthquake warning system, which warns that an earthquake is detected. A deployed network of sensors is capable of giving warning messages and advises on how to react to such warnings. The system has two schemes one is for the Meteorological and Hydrological Service and the other for the general public. The seismic sensor network is deployed at various points in the city, including the coastal zone; these seismometers, detect the P waves (primary longitudinal soil waves) and this information is analyzed by the JMA. Before the arrival of S waves (preliminary waves before a real earthquake) there may be smaller seismic movements and for safety, this information is not made available to the public; but when very strong waves are detected the Warning system distributes the alerts to users thru radio stations, mobile phones, and several other communication channels With the network of sensors deployed throughout the city, it seeks to help people to reduce earthquake damages to the least, allowing them to find refuge or move away from dangerous areas [9].

The present study proposes the design of a scalable, low cost WSN capable of providing channel capacities under different levels of background noise, optimizing node positions using an especial software designed for this effect; this work could be used in future projects to analyze sensors' data from different sensitive structures (i.e. bridges, stadiums and tunnels) and provide effective warnings with the main purpose of saving lives before the occurrence of catastrophes like the April earthquake.

This article is organized as follows. In Section II, the System Model and the main aspects of the employed scenario are presented. In Section III, the Problem Formulation and description of the main mathematical base for this work are introduced. In Section IV, the Proposed Algorithm, the utility functions and the SA algorithm are presented. In Section V, the Results, the analysis of the proposed scenarios and the performance evaluation of the proposed algorithm are given; and finally, in Section V, the Conclusions, mayor contribution and future work are presented.

II. System Model

In this section, the system model used for a building with a WSN deployment in an urban scenario with different levels of noise interference is presented.

A. Scenario

A typical tall building in downtown Guayaquil was selected inside an area where many buildings suffered some kind of affectation due to de April earthquake. In Fig. 1, the selected building is pointed with a red arrow and its name is San Francisco 300.

Fig. 1 Downtown Guayaquil View Signaling Chosen Scenario

On each floor of the building there is a center corridor where three wireless sensors are located. The model is a 30 story building and each floor has the same distribution. Since it is already built the position of the sensors has to deal with this factor and an approximate representation is given in Fig. 2. There will be one coordinator and two sensor nodes per floor, since the building structure is symmetrical for all floors, the coordinators would be located following a vertical alignment maintaining good connectivity from floor to floor. Coordinators and gateway can operate connected to an AC power outlet or from a battery, normally they should be plugged due to power required by their normal tasks, while remote sensors are battery operated, since they can be triggered by events, they can be operative for a long time and its power level monitored by the network. Coordinators and remote sensors in the scenario, are capable of measuring vibrations and smoke. The gateway should be strategically located to obtain the best QoS from data coming from coordinator nodes and be able to communicate information to a central monitoring station outside of the building, either by RF or through fiber optics. Due to the spacing existing from the first floor to the second floor it would be advisable to place the gateway on the second floor, following the vertical alignment with the coordinators on the rest of the floors.

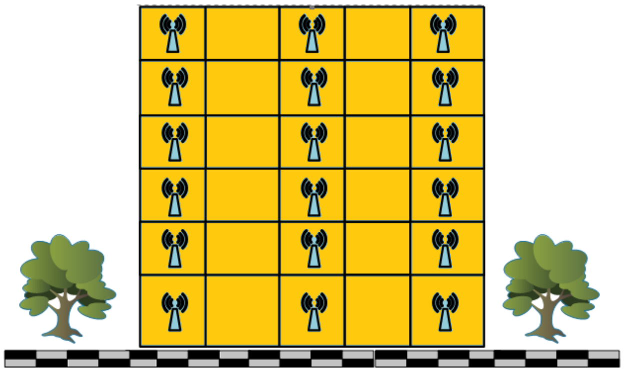

Fig. 2 Sensors per Floor

B. Interference Model

In this particular study, nodes S_i are of ZigBee technology and that they are connected in a mesh topology [10].

Channel topology for these devices is as follows:

As observed in Fig. 3, there are N_z ZigBee channels with a bandwidth of BW_z Hz and a separation of Δf_z Hz. On the same graph, on the Wi-Fi part, AP can use any N_w . overlapped channel of BW_w . Hz bandwidth, with a separation of Δf_w between channels.

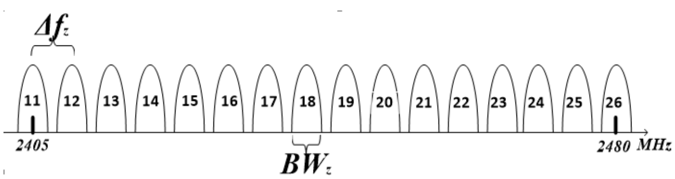

Fig. 3 Channel Assignment for ZigBee

ZigBee could work on the 900KHz band (channels 1-10) or in the 2.4GHz band (channels 11-26); but, those considered for this study, are the ones on the 2.4GHz band, that share the ISM frequency spectrum with Wi-Fi channels working on the same band. Since both technologies use the same ISM band, there could be interferences.

Sensors S_i for the modeled building are optimized along a central corridor that runs across each floor of the San Francisco 300 building, a cluster of three sensors are used per floor. The operation of these sensors are considered for three levels of background noise: a) For urban residential areas; b) for congested residential areas and c) rural areas.

A sensor S_i can be affected by interference of other sensors or by any wireless interference at their location; this is the reason why a previous study was made to determine average random noise values used for this analysis.

The analysis for a pair of sensors S_i and S_j belonging to the same WSN is described as follows:

The Power received by a receiver sensor from a transmitting sensor can be represented as:

$$Pr = Pt + Gt + Gr + L \qquad (1)$$

where *Pr* is the power received in dB, *Pt* is the transmitted power in dB, *Gt* is the transmitter gain in dB, *Gr* is the receiver gain in dB and *L* is the propagation loss in dB.

The propagation losses will be considered from the model COST 231 Keenan and Motley for losses in interiors of walls and floors with similar characteristics, its expression is the following:

$$L = L_0 + 10\gamma \log d + \sum_{i=1}^{I} N_{f,i} L_{f,i} + \sum_{j=1}^{J} N_{w,j} L_{w,j} \qquad (2)$$

Lo are propagation losses at 1 meter of the transmitting antenna in dB, γ is the propagation loss exponent, d is the distance between transmitter and receiver, $N_{f,i}$ is the number of floors with the same characteristics, $L_{f,i}$ are the propagation losses of the signal through the floors in dB, $N_{w,j}$ is the number of walls with the same characteristics, $L_{w,j}$ are the signal propagation losses through walls in dB, I is The number of floor types traversed by the signal and J is the number of wall types traversed by the signal.

Table 1, represents typical values for the loss parameters described in (2).

TABLE I
TIPICAL VALUES FOR WALLS AND CEILING LOSSES

Loss Type	Loss Range (dB)
Lf	13 - 27
Lw1	2 - 4
Lw2	8 - 12

III. PROBLEM FORMULATION

Knowing the importance of the implementation of an early warning system for risk situations through WSN in buildings and given the proposed scenario it is necessary to make the following mathematical formulation:

To carry out a channel capacity analysis in this scenario will be necessary the following metrics.

A. Metrics

One of the metrics used is the signal to noise interference ratio received by a sensor S_j ($SINR_{s_j,s_i}$), which is described as follows:

$$SINR_{s_j,s_i} = \frac{P_{Rx_{s_j,s_i}}}{\sum_{k=1,k\neq i}^{N} I_{s_j,s_k} + \sum_{l=1}^{M} I_{s_j,ap_l} + NOISE} \qquad (3)$$

such that, $P_{Rx_{s_j,s_i}}$ is the power received by sensor S_j from sensor S_i. I_{s_j,s_k} Is the interference from any sensor S_k to the observed sensor S_j. I_{s_j,ap_l} Is the interference from any ap_l from the Wi-Fi network to sensor S_i, *N* is the total number of sensors and *M* is the total number of AP. Finally, *NOISE* represents the background noise of the scenario.

With $SINR_{s_j,s_i}$, it is possible to determine channel capacity as follows:

$$CC_{s_j,s_i} = BW \log_2\left(1 + SINR_{s_j,s_i}\right) \quad (4)$$

in which $SINR_{s_j,s_i}$ is obtained from (3) and BW is the bandwidth of the cannel under use.

Since WSN are being used, it is important to express that, their speed depends on the signal to noise relation that these devices have at the moment of a transmission transaction, allowing a higher or slower channel capacity according to Table II.

TABLE II
WSN SPEED-SINR CHARACTERISTICS [11]

Rb (Kbps)	SINRmin (dB)
250	3
500	6
1000	9
2000	12

IV. PROPOSED ALGORITHM

In this section the process to obtain optimum and reliable communication between motes base on the behavior of signal to noise ratio levels is detailed.

A. *Algorithm Description*

At the beginning of the algorithm, the geographic position of the wireless motes is set with the aid of a GPS. After that the distance between sensors motes are determined then, the transmission power and the gain of receiving and transmitting antennas are considered. With all these data, the power at the receiver is measured. After this the SNR will be calculated, if at least one channel meets the requirements then the mote is correctly positioned, otherwise it must be relocated and a new re-calculation performed. This procedure will be executed for three scenarios a) Low congestion; b) Medium congestion and c) High congestion.

TABLE III
SIMULATION PARAMETERS

Parameter	Value	Unit
Transmission Power	20	dBm
Transmission Antenna Gain	10	dBi
Reception Antenna Gain	10	dBi
Operating Frequency	2.45	Ghz
High Noise Level	-77	dBm
Medium Noise Level	-84	dBm
Low Noise Level	-91	dBm
Floor Losses	27	dB
Thin Wall losses	4	dB
Thick wall losses	12	dB
WSN Bandwidth (BWz)	3	MHz
WSN Peak Freq. Dist. (Δfz)	5	MHz

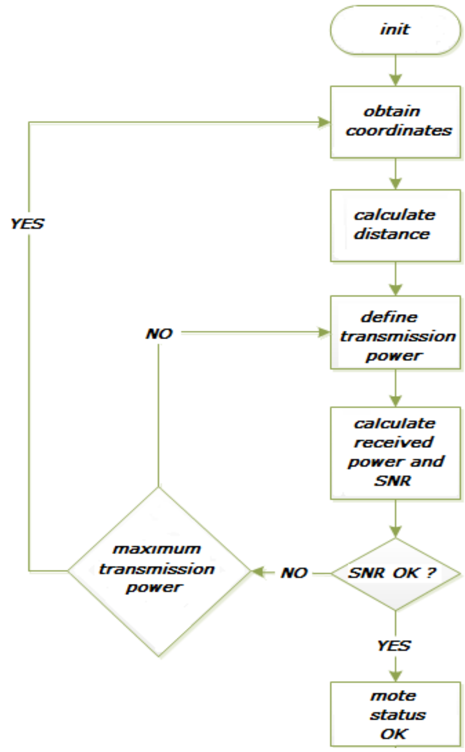

Fig. 4 Algorithm Flow Diagram

V. RESULTS

In this paper the performance analysis of WSN deployments for monitoring the structural health of buildings to prevent disasters in Ecuador was analyzed and proposed for the problem formulation presented in Section III and the System Model of Section II for the WSN characteristics from Table II and the simulation parameters presented in Table III.

It is was expressed at the end of Section III, that WSN speed depends on the signal to noise relation that these devices have at the moment of a communication transaction; higher or slower channel capacities are achieved according to Table II. With these characteristics it is possible to make color representations of the results as observed in Fig. 5 through 7; a channel connection speed of 250 Kbps is shown in magenta, 500 Kbps in green, 1000 Kbps in black and 2000 Kbps in blue according to Table IV.

In the simulation parameters presented in Table IV, it is possible to observe a bandwidth of 3 MHz used by WSN in the 2.4 GHz ISM band. Additionally, different background noise levels are specified: high noise level at -77 dBm, medium noise level at -84 dBm and low noise level at -91 dBm. With these values and the algorithm implemented in Section IV, channel capacities between nodes will be obtained as in formula (4), and the behavior of the links are presented and analyzed for the three noise levels mentioned above to simulate different noise conditions; these values were previously measured in representative places of Guayaquil and its surroundings to give a noise reference for the graphics presented in Fig. 5 through 7.

TABLE IV
WSN SPEED COLORS FOR MATLAB SIMULATION

Speed (kbps)	Color
250	Magenta
500	Green
1000	Black
2000	Blue

The worst case is presented Fig. 5, showing the speed reached by each sensor in a high noise environment. It can be clearly seen that 99% of sensors in the network have a magenta binding link color, representing a maximum transmission range of 250 Kbps. Additionally, given the interference of the scenario, the network can only ensure communication between the sensors located horizontally on the same floor, but not sloping with the rest located on other floors.

In addition, Fig. 6 illustrate the speed reached by each sensor in a medium noise environment. There is an improvement in the transmission speed of sensors with the presence of green and black links, representing additional transmission speeds of 500 Kbps and 1000 Kbps. It is also observed that under medium noise it is possible for sensors to communicate with some other located in other floors.

On the other hand the best case is presented in Fig. 7 showing the speed achieved by each sensor in a low noise environment. In this scenario a total improvement in the transmission speed of sensors is accomplished with the appearance of blue links representing speeds of 2000 Kbps for communication between sensors of the same and different floors.

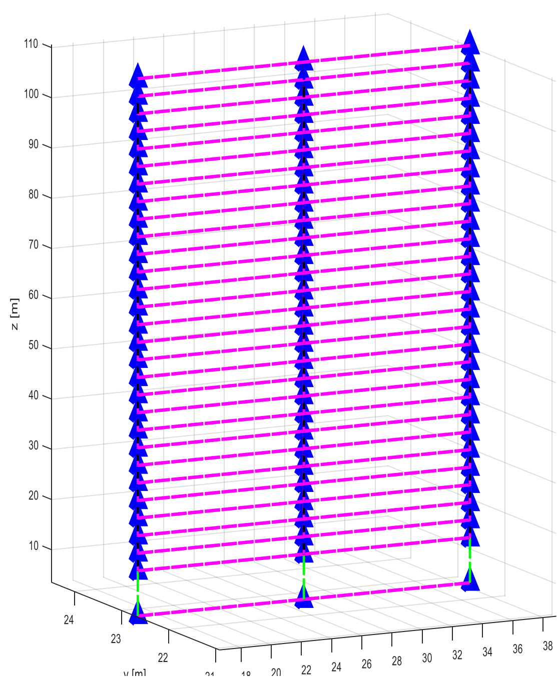

Fig. 5 Simulation of a high noise scenario. Where only 250Kbps links are possible from sensor nodes to coordinators on the same floor, highlighted in magenta. Links between coordinators are kept at 2000Kps (blue) in order to transmit data from floor to floor to reach the gateway.

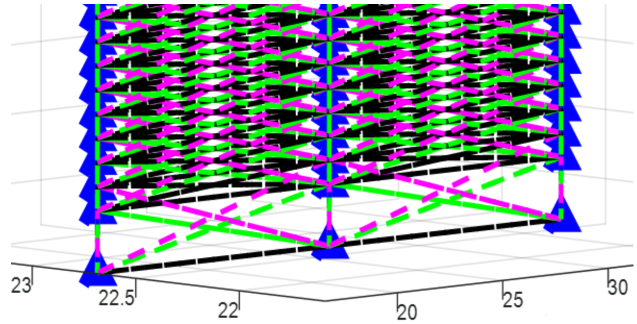

Fig. 6 Close up of the simulation of a medium noise scenario. Where connection links of 250Kbps (magenta), 500Kbps (green) and 1000Kbps (black) are possible from sensor nodes to coordinators on the same floor. Links between coordinators are kept at 2000Kps (blue) in order to transmit data from floor to floor to reach the gateway

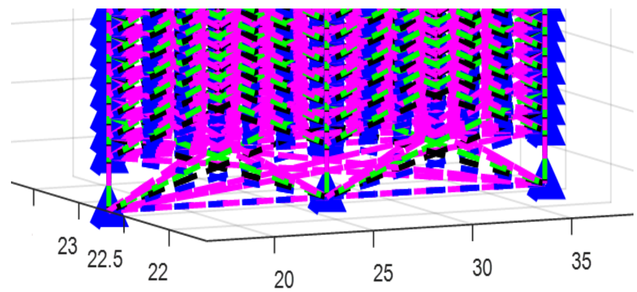

Fig. 7 Close up of the simulation of a low noise scenario. Where connection links of 250Kbps (magenta), 500Kbps (green), 1000Kbps (black) and 2000Kbps are possible from sensor nodes to coordinators on the same floor. Links between coordinators are kept at 2000Kps (blue) in order to transmit data from floor to floor to reach the gateway.

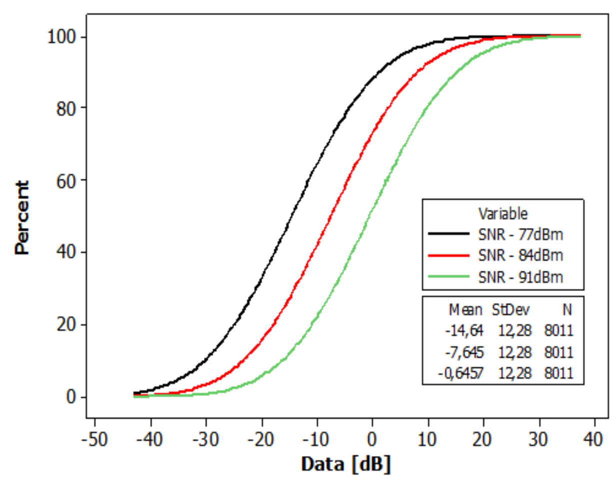

Fig. 8 CDF of SNR of WSN Nodes Links

Finally, it can be seen in Fig. 8 the CDF graph of the sensors behavior in presence of the three noise environments in terms of the SINR. The black color curve has low SINR values since it is the most critical case where the noise levels are high. For the case with medium noise levels, it can be observed how the red graph has better values of SINR. Lastly, the green function shows how the SINR values are improved remarkably due to the presence of the lowest noise levels.

VI. Conclusions

This article enhances the use of WSN in structural health monitoring of buildings to prevent disastrous situations as those occurred with the April earthquake in Ecuador. The implementation of WSN in buildings structures can provide valuable information that could be used to alert people from dangerous situations helping in consequence to preserve lives. In this work, as a first step prior to the design and implementation of WSN in buildings, an analysis of the channel availability of the WSN environment was performed to evaluate its feasibility. Using MatLab software, a WSN was modeled and deployed in a building with three interference environments: high noise, medium noise and low noise. After several simulations and analysis of the obtained results, it was possible to show that communication links and transmission speeds among nodes of the network were affected at different extends at high, medium and low interference, environmental noise scenarios. According to figures 5 through 7, it was possible to observe the variation of the data rates achieved by sensors, going from an initial worst case condition, which for the present design, was capable of allowing data communications at 250Kbps, up to the best case where all speeds were allowed. As future work, new analysis using WSN toward the implementation of a global early disaster warning system in Ecuador are proposed.

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