Analysis and Comparison of IEEE 802.11p and IEEE 802.11bd

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Abstract. As the interest to improve road safety and traffic management is growing, a new generation standard for Vehicular Ad-hoc Networks (VANETs) need to be defined to enhance the performances of the vehicular networks' communications, in terms of reliability, latency, and throughput. Nowadays, the IEEE 802.11p related systems such as ITS-G5, are the most used C-ITS technologies in Europe. However, these radio access technologies (RATs) fall short of supporting many advanced vehicular applications' communication requirements as high reliability, low latency, and high throughput. In this context, the IEEE 802.11bd is being defined as an amendment to IEEE 802.11p to fulfill these requirements. In this paper, we first analyze the introduced mechanisms in IEEE 802.11bd. Then, to assess its performances compared to the IEEE 802.11p, we propose a simulation-based approach by implementing this new RAT in the OMNeT++ simulator. This implementation will be tested and evaluated. We show that IEEE 802.11bd can enhance the network quality of service performance compared to IEEE 802.11p. This will allow improving road safety.

Keywords: Cooperative intelligent transport systems, IEEE 802.11p, IEEE 802.11bd, OMNeT++.

1 Introduction

Vehicular communications have an eminence potential to improve road safety. It allows vehicles to exchange awareness messages with their surroundings. This cooperative aspect will procure a set of applications to build an awareness system for better road safety and traffic management. These messages must be sent reliably, quickly, and with high throughput to promise a better safety service. Nowadays, V2X communication technologies (i.e. ITS-G5 and WAVE) are based globally on the standard IEEE 802.11p™-2010. This latter is derived from the IEEE 802.11a™ -2009. However, during the past decade, IEEE 802.11 technology has been improved, from IEEE 802.11a™-2009, to IEEE 802.11n™-2009, IEEE 802.11ac™-2013 and the ongoing IEEE 802.11ax™ amendment, which offers very high throughput, as well as, improved communication range and higher reliability. So, to benefit from these enhancements and to scale the vehicular performances, a new Study Group called the IEEE 802.11

Next Generation V2X was formed in March 2018 [1] to create the IEEE Task Group 802.11bd (TGbd) in Jan. 2019. This task group aims to build a new V2X communication standard, namely the IEEE 802.11bd standard. This latter will be the definition of new PHY and MAC specifications based on new and existing IEEE 802.11 WLAN PHY/MAC (IEEE 802.11ac and IEEE 802.11ax) standards. The IEEE 802.11bd standard is supposed to replace the IEEE 802.11p standard and to provide a vehicular ad-hoc environment with performance enhancement compared to IEEE 802.11p in terms of throughput, latency, reliability, and communication range.

The IEEE 802.11ac standard was implemented (by Vincenzo Inzillo et al) [2] in the Discrete Event Simulator OMNeT++. This implementation focused on the INET Framework which is an open-source OMNeT++ model suite for wired, wireless, and mobile networks. Implementing the IEEE 802.11ac in OMNeT++ bought improvements in the simulator's features such as the very high throughput (VHT) mode and the multiple-input multiple-output (MIMO) antennas. The IEEE 802.11p standard was implemented in the INET framework too. This implementation was used by the Artery framework [3] as the PHY and MAC layers of the ITS-G5 technology.

The objective of this paper is to provide analysis and performance comparison between IEEE 802.11p and IEEE 802.11bd in meeting the new generation V2X application requirements. We can evoke some theoretical evaluations that treat the same subjects as ours. The finding in [4] presents an evaluation of the performance of V2X technologies by modeling their complete PHY features in MATLAB. Adding to that most studies that dealt with C-V2X performance derived their results from simulation platforms [11]. Our comparison is performed through the OMNeT++ simulation platform. We used the Artery framework to simulate ITS-G5 technology (i.e. IEEE 802.11p. Furthermore, since OMNeT++ doesn't provide an IEEE 802.11bd implementation like many other discrete event based-simulation tools. We will follow the OMNeT++ improvement move and enhance the features of both INET and Artery by implementing the IEEE 802.11bd standard in the INET framework. Thus, make it available in the Artery. We built a basic implementation of the IEEE 802.11bd standard in to be able to simulate IEEE 802.11bd based V2X communications. The remainder of this paper is structured as follows. In Section 2, we will present an overview of each technology with an emphasis on how each of them will enhance message delivery reliability. Next, in Section 3, we will present, in detail, the implementation and validation of the IEEE 802.11bd standard. Finally, we will conclude with a road safety perspective on how these improvements will enhance road safety.

2 Overview of C-ITS Technologies

In this section, we detail the most relevant specifications of each technology that have an impact on the reliability of message delivery.

2.1 Overview of the IEEE 802.11p standard

The IEEE 802.11p is based on the IEEE 802.11a standard, to which it brings some changes to adapt it for the vehicular environment. This standard supports relative velocity up to 200 km/hr, a response times of around 100 milliseconds, and a communication range of up to 1000 meters. However, due to interferences and noise effects, this standard doesn't assure good reliability of message delivery. As presented in [6], the estimated average delivery reliability of IEEE 802.11p is 78%. This is due to the above-mentioned Physical and MAC layers specifications.

The physical layer of IEEE 802.11p is based on the Orthogonal Frequency Division Multiplexing (OFDM) similar to most 802.11 standards. The main difference as compared to IEEE 802.11a is in the carrier spacing and bandwidth, which are reduced by a factor of two (10 MHz of bandwidth and 156.25 kHz sub-carrier spacing). IEEE 802.11p uses binary convolutional coding (BCC) that is a weak coding mechanism compared to the low-density parity-check coding (LDPC) or the turbo coding. BCC loses its capability to recover erroneous messages once we augment the modulation and coding schemas (MCS) in a high communication range (i.e. >50 meters). The MAC layer of the IEEE 802.11p uses the Enhanced Distributed Channel Access (EDCA) method which uses carrier sense multiple access with collision avoidance (CSMA/CA) with no exponential back-off and no message acknowledgment [7]. To provide low latency, the IEEE 802.11p standard is operating in the out-of-context of a basic service set (OCB). This means that there is no association nor authentication before sensing the channel. Besides, the standard does not allow message retransmission. Consequently, a loss in message delivery reliability is observed.

2.2 Overview of the IEEE 802.11bd standard

IEEE 802.11bd standard is based on the IEEE 802.11ac (a.k.a. Wi-Fi 5) which makes it more powerful than its predecessor IEEE 802.11p. According to the project authorization report (PAR) [8], the IEEE 802.11bd standard should assure twice the performance of the IEEE 802.11p with a tolerance for twice the MAC throughput of 802.11p, relative velocities up to 500 km/hr, and twice the communication range of 802.11p. In the IEEE 802.11bd PHY layer, a 20 MHz bandwidth channel is used for communication instead of 10 MHz in IEEE 802.11p. The modulation and coding scheme (MCS) profile can reach 256-QAM, and multiple-input multiple-output antenna can help in providing very high throughput. To maintain reliability in an environment of 500 km/hr velocity and using 256QAM MCS, IEEE 802.11bd uses the LDPC coding mechanism and Midambles which are similar in form to a preamble but are used in-between the OFDM data symbols to estimate the channel variation. Thus, this reduces the interference effects on message integrity. $IEEE\ 802.11bd^{DC}$ is a variant of the IEEE 802.11bd and is based on the IEEE 802.11ax standard. The bd^{DC} implements the dual-carrier modulation (DCM) which augments its communication range. IEEE 802.11bd MAC layer is also based on the EDCA method to access the channel. However, with a 20 MHz bandwidth and a 256-QAM MCS, we can allow message retransmissions by sending each OFDM symbol over two different sub-carriers. This latter, combined with each of LDPC and midambles, will help to achieve better reliability of message delivery as compared to the IEEE 802.11p standard performances.

3 Implementation and Model Validation

In this section, we propose to implement the IEEE 802.11bd important building blocks in the OMNeT++ simulator. Then, we validate our implementation by comparing the simulator's output with the theoretical specification of the standard.

3.1 IEEE 802.11bd Implementation.

The first step of this implementation was to study and test what was implemented as VHT specifications in the physical layer models of the INET framework. Next, we adopt these specifications to build a new "bd" operating mode, that reflects the IEEE 802.11bd standard implementation. Furthermore, we use this implementation in the Artery framework to benefit from an enhanced throughput in our VANET simulation scenarios.

In the INET Framework.
The two micro-layers that are concerned with these modifications are the IEEE 802.11 "mode" modules and the "packet-level" modules. The "mode" modules are both the "IEEE 802.11 mode" module and the "IEEE 802.11 band" module. The "mode" module defines the Modulation and coding schemas (MCS), the number of streams, and the preamble format used to achieve the wanted data rate values. As the "bd" mode requires a Very High Throughput (VHT). We use the "VHT Mode", thus, supporting modulation schemes up to 256-QAM. The "IEEE 802.11 band" module defines the frequency band and its respective channel bandwidth. And as the IEEE 802.11bd operates on a channel bandwidth of 20MHz in the 5.9 GHz band, we had to add the definition of these channel parameters to the "band" module. In Fig. 1, we illustrate the concerned modules in the process of adding the "bd" operation mode. This operation mode had to be added in each of these modules to have a complete PHY layer that can support the "bd" mode.

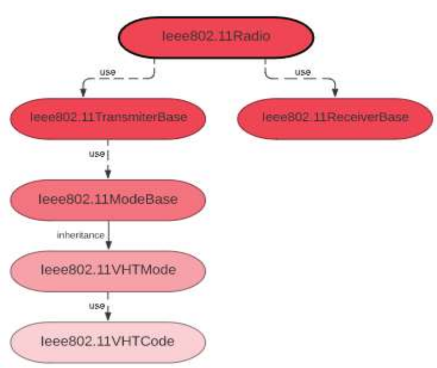


Fig. 1. *The concerned modules with the modifications.*

To be able to send and receive messages in a 20MHz channel bandwidth we had to define a 5.9 GHz band with two 20 MHz bandwidth channels. The 5.9 GHz can hold up to two 20 MHz channels. The central frequencies of these two 20 MHz channels are 5.875 GHz and 5.905 GHz. We defined this band as an "Ieee80211EnumeratedBand" structure that takes as parameters the name of the band and the central frequency of each channel as shown below from the "Ieee80211Band.cc" code source:

```
Const Ieee80211EnumeratedBand
  Ieee80211CompliantBands::band5_9GHz20MHz("5.9 GHz&20 MHz",
  {
    GHz(5.875),
    GHz(5.905),
  });
```

With these modifications done we could modify the OMNeT++ Network Description Files (NEDs) to add the operation mode "bd" and the band name 5 GHz&20 MHz as depicted in the following extract of the "Ieee80211TransmitterBase.ned" source file.

```
module Ieee80211TransmitterBase extends NarrowbandTransmitterBase
{
    parameters:
        string opMode @enum("a", "b", "g(erp)", "g(mixed)",
"n(mixed-2.4Ghz)", "p", "ac", "bd");
        string bandName @enum("2.4 GHz", "5.9 GHz", "5.9 GHz&20
MHz", "5 GHz","5 GHz&20 MHz","5 GHz&40 MHz","5 GHz&80 MHz","5
GHz&160 MHz");
        int channelNumber;
        modulation = default("BPSK");
}
```

In the Artery Framework.
Artery modules are responsible for the Application and the Facilities layers in the ITS station architecture (see Fig. 2). The component that manages the message forwarding between these layers and the lower ones is the Artery middleware, which acts also as an abstraction and data provisioning layer for VANET applications (services in Artery's terminology). Artery provides a flexible framework for the implementation of services (applications). It offers the possibility of creating many services in a VANET node and each service can operate with a multi-channel policy [3]. These services are created according to an external definition as an XML configuration file (services.xml file). This XML file lists the services for a group of vehicles, with their respective port and operating channel numbers. By default, the channel number is set to the Control Channel (i.e. CCH: central frequency = 5.9 GHz) as defined in the ITS-G5 standard.

To introduce the IEEE 802.11bd standard operating mode that we added in the INET framework, we modified the "application", "inet" and "utility" packages of the Artery Framework. The "application" package represents the application layer related modules. The "inet" package represents the modules that are related to the INET framework. The "utility" package represents the definition of some basic elements that are essential for the operation of other Artery modules. To send messages, the Artery middleware needs to find a network interface that operates on the appropriate service's channel. And to receive a message, it needs to find which service should this message be delivered to. If not specified in both the "omnet.ini" and the "services.xml" files of the simulation scenario, the middleware sends and receives messages according to the default parameters (i.e. the IEEE 802.11p network interface). So, to be able to send and receive messages in the newly defined "5.9 GHz&20 MHz" channel, we added its definition in the "utility/channel" module under the name of SCH0_BD and SCH1_BD as listed in the following extract of the "channel.h" source file.

```
constexpr ChannelNumber SCH0_BD = 0;
constexpr ChannelNumber SCH1_BD = 1;
```

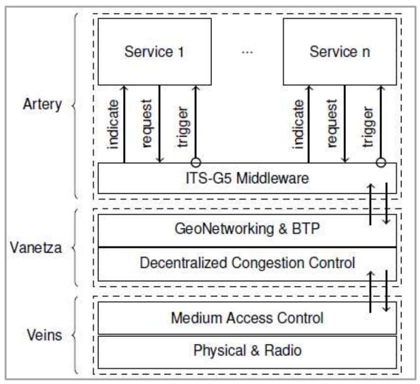


Fig. 2. Artery's ITS architecture [3].

To differentiate between a service that will use the IEEE 802.11p PHY layer and a service that will use the IEEE 802.11bd PHY layer in Artery. We added the "channel-bd" parameter to the service in the "services.xml" configurations file as listed in the following extract of the source file.

```
<?xml version="1.0" encoding="UTF-8"?>
<services>
  <service type="artery.application.CaService">
    <listener port="2001" channel="180" channel-bd="0" />
  </service>
  <service type="artery.application.ExampleService">
    <listener port="4711" channel="180" channe-bd="0"/>
    <listener port="4712" channel="176" channel-bd="1"/>
    <filters>
      <penetration rate="0.5" />
    </filters>
  </service>
</services>
```

To resume this implementation process, we modified both the INET and Artery frameworks to implement the basic specifications of the IEEE 802.11bd standard. In the INET framework, we used the VHT modules from the IEEE 802.11ac implementation to build an IEEE 802.11bd mode-set. We also defined a new 5.9 GHz band, namely the “5.9 GHz&20 MHz”. In the Artery framework, we adapted the service’s definition in the “services.xml” file and the Artery middleware to send and receive messages via a network interface that uses the IEEE 802.11bd standard. The network interface configuration under the “bd” mode is listed in the following extract of the “VanetNic.ned” source file. The “opMode” parameter indicates the IEEE 802.11 standard. Both “bandName” and “bandwidth” parameters define the band used to transmit and receive messages.

```
module VanetNic extends Ieee80211Nic
{
    parameters:
        macType = "Ieee80211Mac";
        mgmtType = "Ieee80211MgmtAdhoc";
        opMode = "bd";
        bitrate = default(52 Mbps);
        **.opMode = opMode;
        mac.modeSet = opMode;
        mac.qosStation = true;
        mac.rx.typename = default("ChannelLoadRx");
        radioType = default("VanetRadio");
        radio.bandName = "5.9 GHz&20 MHz";
        radio.bandwidth = 20 MHz;
        radio.channelNumber = default(0);
        radio.antenna.numAntennas = 8;
        radio.receiverType = default("VanetReceiver");
…}
```

3.2 Model Validation.

Our implementation is intended to make a simulation-based comparison between IEEE 802.11-based C-ITS technologies (IEEE 802.11p and IEEE 802.11bd). This comparison has to be aligned with what was studied in the theoretical and analytical comparisons such as [4]. In this context, we first compare the IEEE 802.11bd theoretical performances with the obtained simulated results in terms of data bitrate (i.e. net bitrate). Next, we compare the performance of this new generation standard with its predecessor IEEE 802.11p in terms of bitrate, latency, and packet reception ratio (PRR) while varying the modulation and coding schemes and the distance between vehicles. Furthermore, to avoid interoperability and fairness issues, we consider evaluating these technologies in an isolated simulation environment. In all the simulation scenarios, we consider an urban road type and we assume that the IEEE 802.11bd standard will be published by the end of 2021 [12]. Simulation parameters are Summarized in Table 1. Our evaluation scenario is based on the Manhattan urban grid road type, where V2V communication is considered according to these characteristics:

- Max vehicle speed: 40 km/h
- Between vehicles Gap: 0.5 m (meter)
- Vehicle acceleration: 0.8 m/s²
- CAM message (Cooperative Awareness Message) and alert/warning messages: 10 messages per second (10 Hz)

Table 1. Main simulation parameter set.

	IEEE 802.11p	IEEE 802.11bd	LTE-V2X
Simulation time	120s		
Message length	From 200 Bytes to 1400 Bytes.		
Channel bandwidth	10 MHz	20 MHz	20 MHz
MCS	Up to 64-QAM with ¾ coding	Up to 256-QAM with ¾ coding	Up to 64-QAM
Num. NSS		1	
Receiver sensitivity	-85 dBm	-85 dBm	-85 dBm
Noise	-110 dBm	-110 dBm	-110 dBm
Receiver energy detection	-85 dBm	-85 dBm	-85 dBm
Transmit power	23 dBm	23 dBm	15 dBm

The throughput depends on the number of data subcarriers, and this latter is tightly related to the bandwidth [4]. So, with a 20 MHz channel bandwidth, we will have 52 data subcarriers out of 64 OFDM subcarriers. With these resources, the IEEE 802.11bd will be able to realize the presented theoretical net bitrate in Table 2.

To calculate the net bitrate ($Rdata$), we used the same equation used in the IEEE 802.11ac standard as presented in [9].

$$Rdata = \frac{N_{DPBS}}{T_{Symbol}} \qquad \text{(Eq. 2)}$$

The N_{DPBS} is the number of data bits per OFDM symbol and T_{Symbol} is the symbol duration. The N_{DPBS} is determined by the number of data subcarriers and the MCS, while T_{Symbol} is determined by the employed bandwidth and the guard interval (GI) [9]. When we implemented the IEEE 802.11bd standard, we defined a set of modes. Each mode represents a combination of a modulation and coding scheme (MCS), a guard interval duration, and spatial streams. Each mode is associated with a specific data rate. After retrieving these simulation data rates and comparing them with the calculated theoretical ones, we found that the simulated bitrate confidently approaches the theoretical bit rate (see Table 2).

Table 2. Obtained simulation results compared to theoretical ones.

Modulation	Coding	Net bit rate (Mbps)	Simulation Net bit rate (Mbps)
BPSK	1/2	7.2	6.5
QPSK	1/2	14.4	13
QPSK	3/4	21.66	19.5
16-QAM	1/2	28.88	26
16-QAM	3/4	43.33	39

64-QAM	2/3	57.78	52
64-QAM	3/4	65	58.5
64-QAM	5/6	72.22	65
256-QAM	3/4	86.66	78

After comparing the calculated net-bitrate and the simulated one, we analyze this metric against the IEEE 802.11p. To do so, we launched two separate simulation runs, one using the IEEE 802.11bd standard (256-QAM), and the other using IEEE 802.11p (64-QAM). In this simulation runs, we vary the packet length from 50 bytes to 1300 bytes, and we fix the distance between two vehicles to 50 meters.

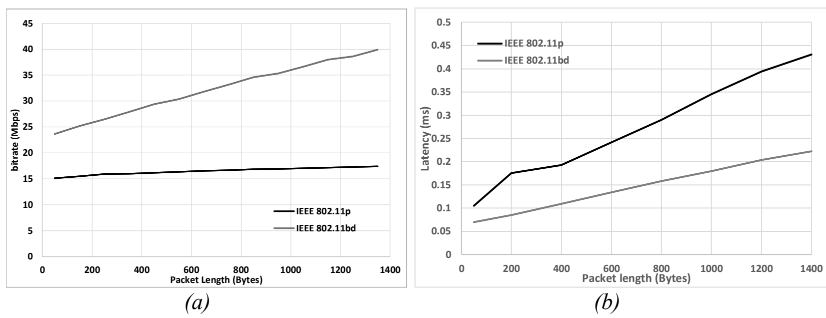


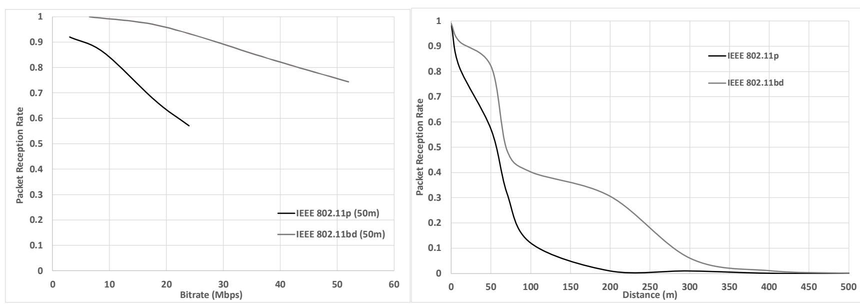
Fig. 3. Throughput (a) and Latency (b) comparison of IEEE 802.11bd and IEEE 802.11p.

From Fig. 3 (a), we can see that the IEEE 802.11bd outperforms IEEE 802.11p in all cases. These results are aligned with the MATLAB ones presented in [4]. In Fig. 3 (b), we recorded a transmission latency of 0.4 ms for IEEE 802.11p and 0.2 ms for IEEE 802.11bd (for a 1200 packet length). Thus, we notice a remarkable transmission latency drop of 50% between the two technologies.

Now that our implementation is validated, we compare the PRR between the IEEE 802.11-based C-ITS technologies (i.e. IEEE 802.11p and IEEE 802.11bd) to make some baselines for the road safety comparison that will follow this work.

3.3 Packet Reception Ratio Comparison

The packet reception ratio (PRR) is defined as the ratio of packets received successfully to the total number of transmitted packets. The PRR is commonly used by the vehicular community to evaluate the maximum range of technology over the distance and to find out how reliable is a technology in terms of packet delivery. To better reflect the performances of the IEEE 80211bd, we compare its simulation PRR results with the IEEE 802.11p ones. At this stage, it is worth noting that our implementation of the 802.11bd standard in OMNeT++ doesn't include LDPC coding. Thus, to obtain an accurate PRR comparison, we have integrated into our simulation results the finding in [10] which affirms that LDCP offers a gain of 1~4 dB over the Binary Convolutional Codes (BCC). This can be translated to a 20% PRR gain over BCC. In Fig. 4 the PRR obtained from different simulation runs is plotted according to the bitrate and to the communication distance. In Fig. 4 (a), we fixed the communication distance to 50 meters to compare the two technologies at the best of their performances. In Fig. 4 (b), we fixed the MCS (2/3 64-QAM) due to Signal to Noise Ratio (SNR) variations. We can observe from Fig. 4 (a) that a higher value of PRR is obtained using IEEE 802.11bd. It is interesting to see that the same values of PRR that can be reached with IEEE 802.11p are reachable by the IEEE 802.11bd with high throughput. In Fig. 4 (b), we can notice that with a value of 64-QAM MCS the PRR of the "bd" is always higher than the "p" one, especially in lower distances.



(a) (b)

Fig. 4. PRR variations according to the bitrate (a) and the communication distance (b).

We can see the outcome of the LDPC coding instead of BCC coding, where an extra 100 meters of communication range, are added compared to the IEEE 802.11p communication range, which is reaching the x-axis at 150 meters.

4 Conclusions

In this paper, we assessed and compared the performances of IEEE 802.11p and IEEE 802.11bd in terms of bitrate, latency, and PRR. First, we implemented the basics of the 802.11bd PHY layer in OMNeT++ simulator, to assess its performance with the 802.11p. Then, to validate our implementation, we compared the theoretical network bitrate, with the simulation-based one. Finally, performance comparison showed that IEEE 802.11bd provides enhanced performance in the OMNeT++ simulator and thus it is more suitable for supporting more V2X applications efficiently. We noticed that a better throughput and low transmission latency are obtained using an IEEE 802.11bd-based PHY layer in Artery. On the other hand, our PRR study demonstrates an average message delivery reliability of 75% for the IEEE 802.11p and 88% for the IEEE 802.11bd. To achieve road safety, several factors should be considered among which the driver's behavior but also the message delivery reliability of the used in-vehicle awareness systems. In this context, and towards a road safety study, we envision using the obtained PRR results to assess the ability of the IEEE 802.11bd to help to avoid more road accidents compared to the IEEE 802.11p. We will also use the road safety

5G Automotive Alliance (5GAA) assessment model [6] to compare the relative performance of the IEEE 802.11p, IEEE 802.11bd, and in regards to improving road safety in the EU roads. Our implementation in Artery was based on INET 3.x version. However, a new version of INET (4.x) is now available but not compatible with Artery. The IEEE 802.11bd implementation source code may be requested by sending an email to one of the authors of this paper.

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