An LTE-based Multicast Scheduling Technique for Critical Smart Grid Communications

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***Abstract*— The management and control of the renewable energy sources in smart grid are currently the most challenging topics in this area of research. Since renewable energy sources are potentially located away from urban areas, cellular communications are most suitable for this purpose. In this paper, we propose an LTE-based priority and delay oriented multicast scheduling technique designed specifically for smart grid management purposes. Using multicast communications in smart grid is most suitable since various messages should be sent to multiple renewable energy sources simultaneously. This is to ensure that these sources are coordinated in performing the same action within a certain time constraint to avoid any power shortages or other issues within the system. We evaluate our proposed technique and compare it with other general purpose multicast scheduling techniques. Results show that the proposed technique offers an enhanced performance over other techniques in delivering smart grid traffic while maintaining good performance for the other real-time traffic, such as voice traffic, within the network.**

Keywords—smart grid, scheduling, LTE, eMBMS

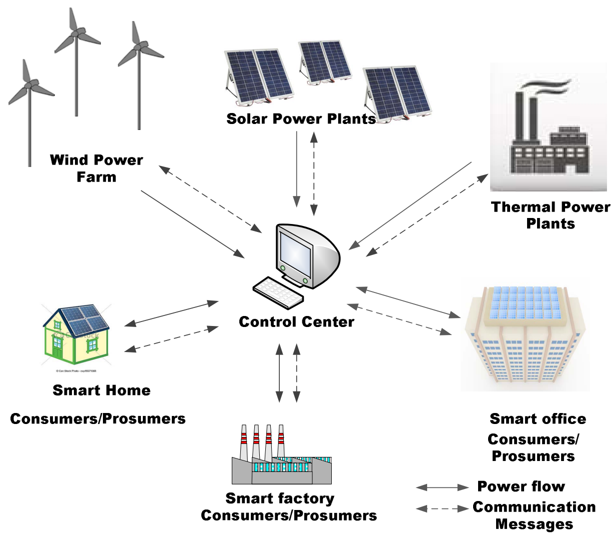

Fig. 1:The smart grid architecture

I. Introduction

The smart grid is an automated electricity grid that optimizes the generation, distribution, and consumption of electrical energy. Renewable energy sources (RES) are the most promising candidates for clean power generation in the smart grid. There are two types of power generators in the smart grid, namely, Distributed Generators (DGs) and Central Generators (CGs). DGs include RES while CGs include regular power plants [1]. Moreover, there are two distributions for RES, namely, large-scale (e.g. wind and solar farms), and small-scale (e.g. wind turbines and photovoltaic panels) [2]. Small-scale power sources are mainly located at the prosumers sites. Prosumers are those grid members who can both consume and produce power. They can consume the generated power from their RES and sell the excess power generated to other consumers. Controlling power generation and distribution in the smart grid is done by a control center as shown in Fig. 1. RES are controlled by an intermediate supervisory controller that decides the timing of using certain sources to balance the demand and generation of overall power. Accordingly, a communication system needs to be used to ensure the robust exchange of the necessary control and management messages between the control center and the elements that constitute the smart grid. These messages include information messages, control messages, billing messages, and emergency messages. Due to the fact that RES are potentially located away from urban areas (e.g. in the desert), the reliance on existing cellular communications infrastructure is considered most suitable for communicating efficiently at a reasonable installation cost over such vast distances.

The management and control communications of the smart grid involves strict delay requirements for the bidirectional message exchange especially those between the control center and the power sources. These messages are classified into two types. The first type is the delay-tolerant periodic messages such as metering and billing information. The second type is the delay-intolerant event-driven messages such as emergency messages, fault alerts and firmware upgrades [3]. The smart grid managers at the control center can observe the consumers' behavior and keep track of the downtime and power failures in the whole grid. The proper selection of an appropriate communication technique is therefore essential for meeting all of these requirements. It is clear from the involved messages that many of them (emergency, control, management) must be disseminated from the control center to the energy sources simultaneously. Failure to do this may cause unpredictable damage to the operation of the smart grid. Therefore, the use of multicast technique seems best suited for such situations.

Long Term Evolution (LTE) is the communication system utilized in state-of-the-art cellular systems. It is the core of 5G and beyond due to its high capacity and native IP support, amongst other factors. The evolved multimedia broadcast multicast services (eMBMS) have been launched by 3GPP in release 8 [13]. eMBMS enables many users to receive the same message simultaneously while efficiently utilizing the communication system resources as compared to multiple unicast transmissions. eMBMS services are mainly intended for multimedia traffic (e.g. video broadcast and online gaming) where massive data rates are crucial for delivering high-quality services to the users. Therefore, its objective is to increase the system throughput. When considering smart grid traffic, we find that the data rates are normally small when compared to those in multimedia traffic. On the other hand, the smart grid traffic is more delay-intolerant compared to the multimedia traffic.

LTE multicast has been previously used in the Demand Side Management (DSM) of the smart grid. The study in [4] proposed a multicast grouping mechanism for efficient power reduction at peak time. This mechanism groups consumers based on their estimated amount of power reduction. The control center sends the message to the consumers with the highest power reduction and finally compare the amount of power reduced with the desired. Due to the limited resources, multicast has been used to reduce network traffic. It was not specified how this multicast will be scheduled over the available resources. In [5], the authors used multicast communication to ensure minimum production cost by sending the multicast messages to those who can decrease their consumption to achieve the least production cost. Moreover, the authors in [6] proposed multicast communication to increase the power reduction by sending multicast messages to users who can achieve highest power reduction. All these techniques are mainly designed for communications between the control center and the energy consumers. In this paper, the target is managing the communications between the large-scale renewable energy farms and the smart grid control center. Many of the existing network scheduling techniques aim at decreasing the communication power consumption and increasing the network throughput. Due to the small-sized high-priority smart grid messages, we propose an eMBMS priority-oriented deadline-based scheduling technique that is designed specifically for smart grid needs. While it meets these needs, it also aims at ensuring that network traffic from sources other than the smart grid is not negatively affected.

The rest of this paper is organized as follows. In Section II, we briefly describe multicast scheduling along with the most relevant existing scheduling techniques. In Section III, we introduce the network model along with the details of our proposed multicast scheduling technique. In Section IV, we present and discuss the simulation results of the proposed technique. Finally, we conclude the study in Section V.

II. LTE-Based Multicast Resource Scheduling

In this section, we discuss the eMBMS resource structure for general multicast communications in LTE. In addition, some of the LTE-based multicast scheduling techniques, that have been introduced in previous studies, are presented below.

A. eMBMS resource structure

The downlink transmission scheme of LTE is based on OFDMA. A physical resource block (PRB) is the building block of resource allocation in LTE. The radio resources are assigned in time and frequency domains. A single frame has 10 sub-frames (SFs). The duration of each SF is 1 ms. Each SF has two slots of 0.5 ms. Each SF is composed of 12 subcarriers. Each subcarrier is of size 15 kHz and has 7 symbols. This means that an SF consists of 84 resource elements. A resource element constitutes the smallest modulation structure in LTE. Extended cyclic prefix (ECP) is applied for Multimedia Broadcast multicast service Single Frequency Network (MBSFN) transmission. In ECP, there are only 6 symbols, i.e. 72 resource elements [7].

The latest 3GPP standard only allows at least one SF and at most 6 SFs for multicast communications out of the 10 SFs [8]. eMBMS frame structure is shown in Fig. 2. After reserving the required SFs for multicast, the remaining SFs are left for unicast transmission.

B. eMBMS scheduling techniques

Many of the scheduling techniques used for eMBMS aim at increasing the system throughput and fairness. The target is to send high quality multimedia content to users to ensure their satisfaction. The Conventional Multicast Scheme (CMS) [9] groups the multicast users who will receive the same data together. In CMS all users receive data with the rate of the user in the group who experiences worst channel conditions. Therefore, users of high channel conditions suffer from being grouped with users of low channel conditions. In many studies, authors investigate the best subgrouping of multicast users to avoid mixing users of significantly different channel conditions in one group. In [10], the subgroup configuration which is based on maximizing the system capacity ensures that all users will be able to demodulate the message, and optimize a cost function. The study proposes a minimum dissatisfaction index (MDI) within this function besides maximizing throughput and proportional fairness. In [11], the study optimizes the resources and a proportional fair utility for multicast and unicast users. The users in this technique are sorted in an ascending order based on their channel conditions. Then a search is done to identify the best subgrouping that fulfills fairness and maximum utility of the system.

Nevertheless, in [12] multicast users are scheduled according to several parameters such as the number of users in the group, the channel quality indicator (CQI) and the price paid by each user for receiving the service. All users of the same class who want to receive the same video are grouped together. The main disadvantage of this technique lies in the fact that high-class groups of small users are served before groups of many users but of lower classes. In [13], the study introduces the Shortest Remaining Time Next (SRTN) scheduler where the requests are sorted in an ascending order according to the remaining packet delay to avoid missing the packets' deadlines. The drawback of this technique is that it does not consider the priority of the message. In [15], the Round Robin (RR) scheduler is described, where the users

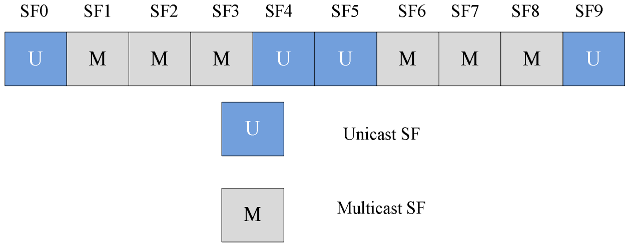

Fig. 2: eMBMS frame structure

are selected at random from the queue and served in a cyclic order. It does not take the channel conditions into consideration. The selection of resource blocks is done according to first come, first served strategy. RR ensures fairness among users. The disadvantages of RR that it does not consider packet deadlines or priorities.

In our proposed scheduling technique, we address some of the disadvantages of the previous scheduling techniques including packet deadlines and priorities. In the smart grid situation, the encountered data rates are much smaller compared to those of videos and online gaming applications. Therefore, subgrouping users on the basis of the modulation and coding scheme (MCS) of users is not efficient.

Hence, CMS is adopted where all users who should receive the same message are placed in the same group. Accordingly, they receive the data at the rate of the worst user's MCS in the group. However, smart grid data has minimum delay and priority requirements for each message to avoid faults or blackouts in the system. Therefore, we propose a priority and delay oriented scheduling scheme.

III. PROPOSED MULTICAST DOWNLINK SCHEDULING TECHNIQUE DETAILS

A. Network model

In this paper, we focus our study on smart grid communications as part of the larger cellular communication system. In particular, RES of the smart grid are considered. These sources are generally composed of smart wind power farms and solar panels power systems. Moreover, we assume the presence of other regular cellular system users whose traffic include different types such as voice, http and ftp. Fig. 3 depicts the targeted network model.

The RES of the smart grid communicate with the control center via intelligent electronic devices (IEDs) that are installed along the grid transmission lines and within its substations [14]. IED connections could be either wired or wireless [15]. In this work, wireless IED connection is considered. Using these IEDs, each station can respond to any request automatically without any human intervention [16]. When an IED receives a command from the control center, it sends a message to the switches of the energy sources to turn on/off in order to manage the power generation [17].

B. The proposed technique

The control center of the smart grid normally sends the same message type and content to several power generation stations. The goal is to ensure that they all receive this message and react to it simultaneously. Therefore, it is most efficient to use multicast communications for this purpose. Hence, we propose a scheduling technique that handles these communications, along with the traffic of the other users within the cellular system, while considering the critical requirements of the smart grid traffic.

In the proposed scheduling technique, the smart grid messages are classified into three categories according to their priority that is based on the delay requirements of each message type [18], as shown in TABLE I. The three categories are gold, silver and bronze. The gold category has the highest priority and least minimum permissible delay while the bronze category has the least priority and highest permissible delay. The minimum delays are determined by the standard IEC 61850 [17], [18]. IEC 61850 is an international standard for defining communication protocols for IEDs at electrical substations. Users are scheduled in time domain such that the users with the earliest deadline are scheduled first, while taking their priority into consideration. Then, the best PRB for each user is determined and assigned in the frequency domain. Algorithm I, illustrates the functionality of the proposed technique.

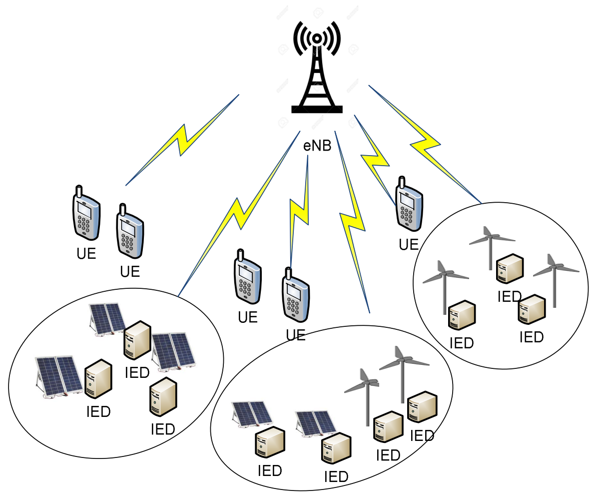

Fig. 3:Network model

TABLE I. THE MESSAGE CATEGORIES CLASSIFICATIONS

Type of messages	***Priority***	***Delay required [ms]***	***Traffic Type***
Messages require immediate actions at receiving IEDs	1 (Gold)	3	Multicast
Faults and other emergency situations	2 (Gold)	10	
Messages require medium transmission speed	3 (Silver)	100	
Messages for slow speed auto control function	4 (Bronze)	500	
Voice	5	100	Unicast
http	6	300	
ftp	6	300	

Algorithm I: Proposed multicast scheduling technique

```
Initialize the SF number ( F= {1, 2,…..10})
Multicast SF (MF = {1, 2, 3, 6, 7, 8})
For i =1: T
F=0
Groups (i) = [G1, G2, G3, ……]
Users (i) = [U1, U2, U3, …….]
RQ (i) ⟵ [Groups no (i); Users (i)]
Sorted matrix ⟵ sort (RQ (i))
If F=MF
  Served users (i) ⟵ Groups no (i)
    If Served users < PRBs
        serve unicast users
     End
 Else
    Served users (i) ⟵ Users
End
PRB assigned for each ⟵ FDS (served users)
Not served users ⟵ RQ (i) –Served users (i)
RQ (i+1) ⟵ RQ (i+1) + Not served users (i)
F=F+1
If F = 10, F ⟵ 0
End for
```

At every Transmission Time Interval (TTI), the following steps are carried out.

Step 1: All smart grid IEDs that are to receive the same message are added to the same multicast group.

Step 2: All requests from unicast and multicast users are arranged in an ascending order according to the earliest deadline missing. Parties that have the same deadline are sorted according to their priority.

Step 3: The multicast users are served first in the multicast SFs and then the remaining PRBs, if any, are assigned to unicast users. This is done according to the priority rules mentioned earlier. In the other SFs all PRBs are assigned to the unicast users. The data rate for each multicast group is determined by the worst user's rate within the group. The rate of a unicast user is calculated based on the CQI as per the PRB assigned to the UE.

Step 4: In time domain scheduling, the scheduler selects the first set of users which is equal to the number of the available PRBs.

Step 5: In the frequency domain scheduling, we aim to maximize the total rate also. Hence we assign the best PRB for each of the served multicast and unicast users. The optimization problem for PRB allocation is as given in (1) with the constraint in (2), where R_j is the data rate of each unicast and multicast user, A_{ij} is the allocation matrix, and x_j is an indicator that equals 1 when a PRB is assigned to a user *j* and equals 0 otherwise.

$$Maximize\ \sum_{j=1}^{n} R_j x_j\,, x_j = 0\ or\ 1 \qquad (1)$$

$$\text{s.t.} \quad \sum_{j=1}^{n} A_{ij} = 1, \qquad (2)$$

The constraint in (2) ensures that the summation of any row vector or column vector for the allocation matrix is equal to 1 to ensure that each PRB is assigned to only one user.

This optimization problem could be solved by using binary integer linear programming optimization. This is based on user CQIs which are used to determine the best PRB assignment that guarantees highest possible rate for each user.

Step 6: The unserved users in the current TTI are pushed to the next TTI if their deadlines have not yet expired.

IV. Simulation and Results

Several simulations have been conducted to evaluate the performance of the proposed scheduling technique by using MATLAB. The network arrangement used in the simulation is as shown in Fig. 3., where all IEDs that should receive the same message are placed in the same group. The other UEs receive regular unicast traffic. Table II shows the default simulation parameters. The smart grid traffic packets are mostly smaller in size than the regular UE traffic. Therefore, any smart grid packet will be served in only one PRB. Table III shows traffic parameters of the system. The smart grid traffic parameters have been defined similar to the study in [19].

The proposed technique is compared with a Round Robin (RR) based scheduler [15], [20] and the Shortest Remaining Time Next (SRTN) scheduler [13]. We also compare the proposed technique with the case where the smart grid messages are sent using unicast transmissions. This is denoted by "unicast" in our simulation results.

The Request Queue (RQ) includes all unicast and multicast packets that have arrived and are to be serviced in the current TTI. The scheduler determines the order of execution of the services according to its own criterion and will select only the ones who will be served in current TTI.

The schedulers are evaluated using the following performance metrics

- Throughput: It is the total number of bits send from the eNB to its destination successfully each second.

  Throughput=

$$\frac{Total\ number\ of\ successfully\ transmitted\ bits}{Simulation\ time} \qquad (3)$$

- Deadline Missing Percentage: The packet delay is first calculated by the difference between the time the packet is sent from the eNB to the time the packet reaches its destination. Then get the sum of the packets that exceed its delay requirement. Finally, the deadline missing ratio is computed by the following formula

  Deadline missing percentage =

$$\frac{Total\ packets\ exceed\ its\ minimum\ delay}{Total\ packets\ generated} \times 100 \qquad (4)$$

The performance of the proposed scheduler has been examined when increasing the number of messages that will be sent from the eNB to the IEDs at different values of system bandwidth. Fig. 4 shows the deadline missing percentage

TABLE II. DEFAULT SIMULATION PARAMETERS

Parameters	Values
System bandwidth	1.4 MHz / 3MHz / 5MHz
No of available PRBs	6 PRB / 15 PRB / 25PRB
Cell radius	1 Km
Total number of IEDs	500
Number of UEs	20 for each of voice, http , and ftp
Number of multicast messages	From 2 to 14 per second per IED
Number of cells	1
Cyclic prefix	Extended
Simulation time	10000 TTIs

TABLE III. TRAFFIC PARAMETERS

Device Type	Traffic Type	Average data rate	Packet Arrival rate (sec^{-1})
IED	Messages require immediate actions at receiving IEDs	9.6-56Kbps (Packet size = 25 Bytes)	5
	Faults and other emergency situations		5
	Messages require medium transmission speed (control commands)	9.6-56Kbps (Packet size = 150 Bytes)	5
	Messages for slow speed auto control function	9.6-56Kbps (Packet size = 200 Bytes)	10
UE	Voice	64 Kbps	25
	http	100 Kbps	25
	ftp	3072 Kbps	300

when varying the number of messages from 2 to 14 messages per second for each IED that should be transmitted. The figure shows that as the number of smart grid messages increases, the percentage of packets that miss the deadlines increases slightly until a certain limit when the increase becomes more noticeable but still within acceptable levels. The figure also shows that with higher system bandwidth, where more PRBs are available, the percentage of deadline missing decreases.

The performance of the new scheduler has been compared with those of other scheduling techniques. Fig. 5 shows the deadline missing ratio for all the different scheduling algorithms. A comparison is done for both types of traffic; the smart grid traffic and the regular user traffic (voice, http and ftp) for an average of 5 different smart grid messages per second for each IED using a system bandwidth of 1.4 MHz. As shown in the figure, compared with the other schedulers, the proposed technique has better performance for both smart grid and regular traffic types. The unicast transmission is the worst as it sends the smart grid messages to each destination individually. This cause many packets to exceed their deadlines. With the RR scheduler, the users are served in a cyclic order without considering packet deadlines or priority causing the deadline missing ratio to be considerably higher than the proposed scheduler. In case of SRTN, the packets are sorted in a packet deadlines ascending order. It does not consider message priority which causes much of the smart grid traffic to exceed the delay requirements. In case there are two users whose packets have the same remaining time, they get sent in a cyclic order without taking their priority into consideration. On the other hand, in the proposed technique, both the remaining time and priority are taken into consideration. Therefore, if there are two packets with the same minimum delay, they get scheduled according to their priority. Compared to SRTN, the deadline missing ratio of the proposed technique is better by 50% for smart grid traffic and by 18% for the voice traffic of regular network users. It is worth mentioning that the proposed scheduler improves the deadline missing ratio for voice traffic by giving real-time UE traffic a higher priority over non real-time traffic (ftp and http).

Concerning the system throughput, Fig. 6 shows the overall throughput for all the algorithms. The figure shows that the throughput of the proposed technique is not high as other multicast schedulers because it gives priority to smart grid devices where its packet size is smaller compared to regular traffic packets. The throughput of the unicast scheduler is the smallest as unicast serves users by taking the minimum delay and priority into consideration. Therefore, smart grid traffic is scheduled first with its small size compared to the regular traffic. In addition, and unlike multicast based schedulers, the unicast scheduler sends the message to each IED individually so more system resources are used and most of them are for smart grid traffic which is of small packet size thus reducing the throughput further. The throughput of RR is the highest as RR schedules the multicast and unicast traffic in a cyclic manner leading to the selection of regular traffic more often than smart grid traffic which increases the system throughput.

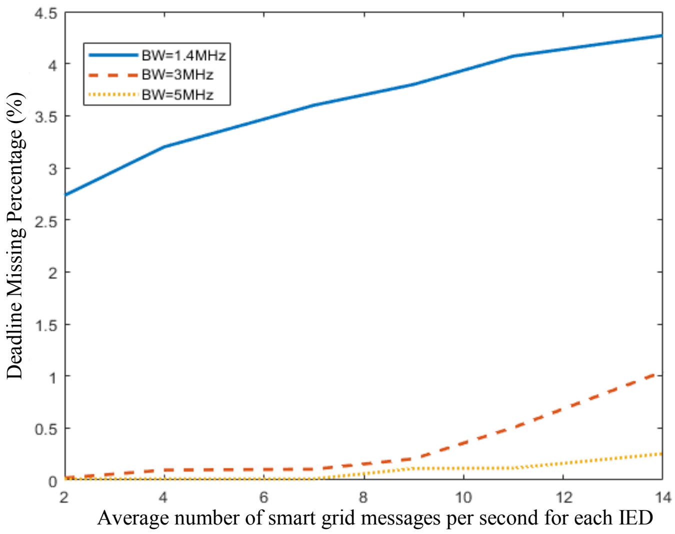

Fig. 4:Deadline missing for multicast messages of the proposed technique versus different number of smart grid messages

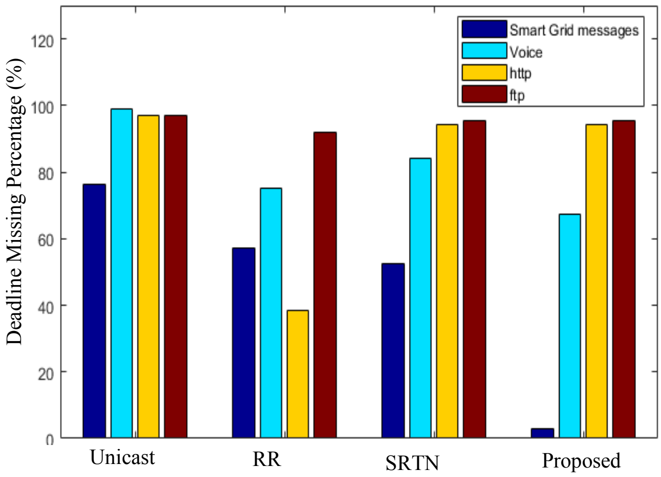

Fig. 5:Comparison between the deadline missing percentage of (unicast, RR, SRTN, and proposed) schedulers

For SRTN the throughput is smaller than RR but greater than the proposed technique. This is due to the fact that SRTN serves smart grid traffic more than RR due to the minimum delay requirements policy that it follows

V. CONCLUSION

In this paper, we introduced an LTE-based priority and delay-oriented multicast scheduling technique designed specifically for smart grid management purposes and needs. The steps of the algorithm have been presented along with the system performance metric. The performance of the proposed technique has been compared to those of other existing multicast scheduling techniques as well as a unicast-based scheduling technique. All of the techniques have been modeled and evaluated with respect to the deadline missing percentage and throughput. Simulation results showed that the proposed scheduler performs better than the other schedulers for both smart grid and regular real-time data traffic. In addition, our technique improves the deadline missing percentage by 50% from the proceeding technique with smart grid traffic. Moreover, it achieves approximately 18% better than the previous technique with regular real-time network traffic. This shows that the regular network traffic is not affected negatively by the way the new technique handles the smart grid traffic.

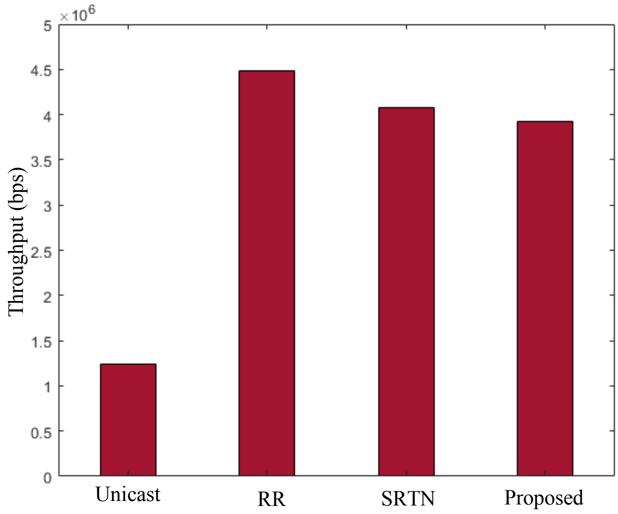

Fig. 6:Comparison between the throughput of (unicast, RR, SRTN, and proposed) schedulers

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