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RESEARCH ARTICLE

Radar-Aided Communication Scheduling Algorithm for 5G and Beyond Networks

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ABSTRACT Radar and communication coexistence is an upcoming technology with numerous research opportunities in the medium access control (MAC) layer, particularly in scheduling and radio resource management (RRM). More efficient scheduling algorithms are needed with the wide range of applications that the wireless environment is experiencing. We investigate an echo-based scenario in the radar-aided vehicular communication system in which an echo is reflected from a target. Unlike the conventional scheduling mechanisms where signal-to-interference-plus-noise ratio (SINR) is exploited, this paper proposes a new radar-aided communication scheduling algorithm by utilizing parameters such as range and velocity with the classical SINR measurements. The proposed algorithm schedules the available resources by extracting information from the radar echo. The proposed radar-aided communication scheduling scheme provides a more flexible design by adding new parameters, resulting in a more efficient algorithm in a broad variety of scenarios. The proposed scheme is beneficial for B5G communication systems that allow localization and sensing as key features of next-generation wireless networks.

INDEX TERMS Radar-aided communication scheduling, range, medium access control (MAC), radio resource management (RRM), scheduling, signal-to-interference-plus-noise ratio (SINR), velocity, 5G new radio (NR), beyond (B5G).

I. INTRODUCTION

Different 5G services have various Quality of Service (QoS) requirements in terms of bandwidth, latency, packet loss rate, and reliability [1], [2], [3], [4]. In 5G and beyond (B5G) radio access technologies (RATs), efficient and flexible schedulers are needed to meet the diverse requirements of the future RATs. The general purpose of most traditional schedulers is to exploit channel variations between user equipments (UEs) and, preferably, to schedule transmissions to a UE when channel conditions are favorable. At the very least, most scheduling strategies require information about UE's channel conditions, buffer status and priorities of the different data flows, and the interference situation in neighboring cells. Medium access control (MAC) is used for scheduling information reporting. The scheduling strategy is implementation-specific and does not conform to the 3rd Generation Partnership Project (3GPP) specifications.

Different UEs may experience diverse radio conditions at a certain time in the mobile network environment. In many scenarios, system capacity can be increased by the low fairness schemes of conventional scheduling algorithms. These algorithms increase the prioritization of UEs with good channel conditions. On the other hand, UEs with average or bad radio conditions cannot be scheduled. The conventional schedulers enable higher data rates due to a tradeoff between UEs fairness and system capacity. The Mobile Network Operators (MNOs) demand consistent UE and system data rates with the minimum QoS requirements. Besides the UE requirements, network radio resource capacity is an essential issue for the

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existing mobile network operations, which cover the whole network life cycle management, such as capacity monitoring, optimization, and expansion. More specifically, the MNOs seek more efficient schedulers while considering commercial scheduling methods such as Proportional Fair (PF), Round Robin (RR), and Best Channel Quality Indicator (BCQI) [5]. MNOs need more and more radio resources due to the growing traffic in their current commercial mobile networks. The lack of radio resources affects the user experience of MNOs. The increasing traffic demand requires efficient schedulers in network radio resource usage.

Base station (BS) allocates fewer resource blocks (RBs) to UE transmitting at a higher rate during resource scheduling. UEs with greater signal-to-interference-plus-noise ratio (SINR), in particular, can use high-order modulation and coding techniques [6], [7], [8]. SINR is used for packet scheduling as a measurement of channel quality. SINR is measured by UE on an RB basis in 5G new radio (NR). SINR is not defined in 3GPP specifications; it is UE vendor-specific, and it is used a lot by MNOs [8]. SINR information is readily available on many commercial radio chipsets [9]. The SINR value for each RB is measured by all UEs and transmitted to the BS. This information is used by BS to make critical scheduling decisions.

As we are heading towards B5G, introducing flexible schedulers that exploit different parameters besides SINR is crucial. Futuristic applications such as vehicle-to-everything (V2X) communication and indoor localization depend on collaborative functionalities of communication and sensing [10]. Proposing a scheduler leads in paving the way toward emerging technologies such as the coexistence of communication and sensing. Leveraging radar sensory data at the communication terminals provides crucial awareness about the surrounding environment. An efficient way to acquire this awareness is by using low-cost radar sensors such as those initially designed for radar applications [11] or by leveraging joint communication-radar systems [12], [13]. The use of radar signals for improving communication has been studied in [14], [15], [16], [17], [18], and [19]. With this motivation, this paper investigates the potential of leveraging radar sensory data to guide the scheduling problem and provides the first real-world demonstration for radar-aided scheduling in a practical vehicular communication scenario. Our key idea is to use the information from the radar operating in a mmWave band to extract the scheduling information where communication happens. The developed solution leverages domain knowledge for radar signal processing to extract the relevant features fed to the communication modules.

Several physical layer (PHY)-based resource management options for radar and communication coexistence have recently been proposed, including power allocation, spatial beamforming, spectrum sharing with waveform design, and time sharing. Figure 1 illustrates the existing work in PHY and the proposed MAC-based work. The following deficiencies exist in the literature: essential principles and important performance measures linked to resource management are not adequately given [20]. The related radio resource management (RRM) studies for radar and communication coexistence systems are classified according to the resource management issues, i.e., spectrum sharing, power allocation, and interference management. Literature works have not been done on the radar-aided communication system in the MAC layer to the best of our knowledge [20]. The radio resource allocation and scheduling issues are not thoroughly explored and debated. Different from the existing PHY-based resource management approaches [20], we propose a new scheduling algorithm tailored for the radar-aided communication systems by exploiting different parameters that have not been used before, which includes; range and velocity. The proposed solution provides a more flexible scheduling mechanism for the systems' available resources. This paper explains in detail how the estimated parameters can aid RRM, including a novel radar-aided communication scheduling mechanism.

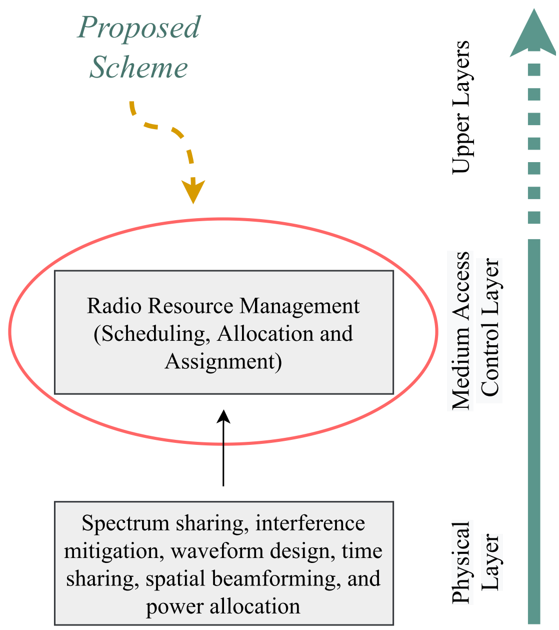

FIGURE 1. Existing PHY-based work in the literature and the proposed MAC-based work.

The proposed scheduler is evaluated by analyzing its performance with the conventional resource scheduling algorithms. Classical physical resource block scheduling algorithms for the resource allocation are reviewed exhaustively in [21]. The UE scheduling concept based on fairness and reliability has been extensively studied in the literature [22], [23]. PF, RR, and BCQI are the most known scheduling algorithms. Our scheduler output maximizes the system performance of the communication system by maximizing its performance metrics, including communication data rate, spectral efficiency, and system throughput. Higher data rate and spectrum efficiency are required in indoor scenarios [24]. Spectral efficiency should be maximized, for example, if an unmanned aerial vehicle (UAV) covers a high

TABLE 1. List of abbreviations.

Abbreviations	Definition
BCQI	Best channel quality indicator
BS	Base station
B5G	5G and beyond
CSI	Channel state information
FMCW	Frequency modulated continuous wave
KPIs	Key performance indicators
MAC	Medium access control
MNOs	Mobile network operators
NR	New radio
PF	Proportional fair
PHY	Physical layer
PSD	Power spectral density
QoS	Quality of service
RAT	Radio access technology
RBs	Resource blocks
RR	Round robin
RRM	Radio resource management
SINR	Signal-to-interference-plus-noise ratio
SLS	System level simulation
SE	Spectral efficiency
TTI	Transmission time interval
3GPP	3rd Generation Partnership Project

number of targets so the scheduling data can be adequately collected. High system throughput is required due to its high reliability: Transmissions occur with a probability of 99.999% as in the V2X scenario [25]. In the V2X scenario, system throughput should be maximized to minimize collision probability.

Our main contributions are summarized as follows:

- For B5G networks, we propose a new radar-aided communication scheduling algorithm.
- We developed and demonstrated, for the first time, the feasibility of radar-aided mmWave scheduling approaches in the real-world scenarios.
- The proposed scheduler is investigated based on the defined communication and radar coexistence applications and the acquired radar echo parameters.
- We evaluate the performance of the proposed scheme in terms of system throughput, spectral efficiency (SE), and data rate.

The merits of the proposed scheme can be stated as follows:

- We obtain a robust performance considering the conventional scheduling algorithms.
- A key feature of the proposed approach is that it incurs a reduced signaling load due to the nature of the radar echo signal that provides scheduling information and reducing the overhead of control channels.
- The proposed scheduler does not require changes in the per-UE scheduling policies implemented by BSs.
- The proposed scheduler fits different scenarios in B5G.

Table 1 shows the list of abbreviations. The remainder of this paper is presented as follows. The system model is explained in Section II. The proposed scheme is illustrated in Section III. Simulation results are discussed in Section IV. Finally, the paper is concluded in Section V. [1]

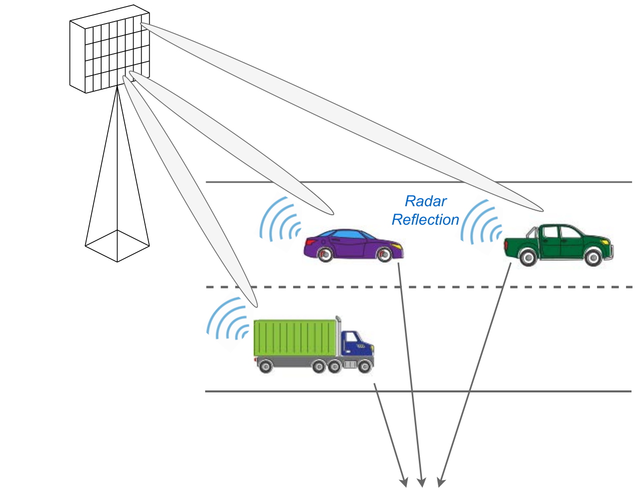

FIGURE 2. The system model where the radar information at the BS is leveraged to schedule the resources of multiple mobile users.

II. SYSTEM MODEL

We investigate a radar echo-based scenario where a radar echo is reflected from the radar target [20]. In this scenario, the echo is exploited to obtain different scheduling parameters, such as target(s) range, velocity, and SINR information. We consider a mmWave vehicle-to-infrastructure (V2I) communication system, e.g., supported through 5G cellular network, where mmWave BSs serve as infrastructure for V2I communications. A monostatic radar system is collocated on the BS, which receives the radar echos from the surrounding targets, as illustrated in Figure 2. When a moving target is detected by the radar, the raw echo signal is sent to the communication module at the BS. Side information derived from radar mounted on the infrastructure operating in a given mmWave band is used to schedule the available resources of the vehicular communication system [5]. The objective of the considered system is to schedule the available resources in the BS relying on information extracted from the radar echo.

The system under consideration in this study comprises of a BS and multiple mobile users which act as radar targets and also as communication receivers. The BS has two major components: (i) A phased array-equipped mmWave communication terminal to communicate with the mobile users, and (ii) a collocated radar system using frequency modulated continuous wave (FMCW) signal. The system and signal models of the communication and radar components are briefly described in the next two subsections [5].

[1] Notation: Matrices and column vectors are represented by bold, capital and lowercase letters, respectively. $(.)^H$, $|.|$, and $\mathbb{E}[.]$ represent Hermitian transposition, absolute value, and expectation operations, respectively.

A. RADAR MODEL

In the considered system, the BS adopts an FMCW radar signal. The objective of this radar is to provide sensed observations of the surrounding environment. The FMCW radar achieves this objective by transmitting chirp signals whose frequency changes continuously with time. More specifically, the FMCW radar transmits a linear chirp signal starting at an initial frequency f_c and linearly ramping up to $f_c + \mu t$, as given by [5]

$$s^{tx}_{chirp}(t) = \begin{cases} \sin\left(2\pi\left[f_c t + \frac{\mu}{2}t^2\right]\right) & \text{if } 0 \le t \le T_c \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $\mu = B/T_c$ is the slope of the linear chirp signal with B and T_c representing the bandwidth and duration of the chirp.

A single radar measurement is obtained from the frame of duration T_f. In each frame, A chirp waves are transmitted with T_s waiting time between them. No more signals are sent until the end of the frame after the last chirp is transmitted. The transmitted signal from the radar frame can be expressed as [5]

$$s^{tx}_{frame}(t) = \sqrt{\mathcal{E}_t} \sum_{a=0}^{A-1} s^{tx}_{chirp}\left(t - a\left(T_c + T_s\right)\right), \quad 0 \le t \le T_f \quad (2)$$

where $\sqrt{\mathcal{E}_t}$ is the transmitter gain. The given transmitted signal is reflected from the target(s) in the environment, and the echo(s) are received back at the radar.

At the receiver, a quadrature mixer mixes the transmit and receive signals to produce the in-phase and quadrature samples. Following that, the combined signals are applied to a low-pass filter. The resulting signal, known as the intermediate frequency (IF) signal, represents the frequency and phase difference between the transmit and receive signals. If a single object exists in the environment, then the receive IF signal of a single chirp can be written as [5]

$$s^{rx}_{chirp}(t) = \sqrt{\mathcal{E}_t \mathcal{E}_r} \exp\left(j2\pi\left[\mu\tau t + f_c\tau - \frac{\mu}{2}\tau^2\right]\right), \quad (3)$$

where $\sqrt{\mathcal{E}_r}$ is the channel gain of the object, which depends on the path loss and radar cross section, $\tau = 2d/c$ is the round-trip delay of the reflected signal through the object, where d represents the distance between the object and the radar, and c denotes the speed of light.

The receive IF signal, s_{chirp} is then sampled at the sampling rate of the analog to digital converter (ADC), f_s, producing S samples for each chirp. Finally, the ADC samples from each frame are collected. For an FMCW radar with M_r receive antennas, each having the described RF receive chain, the resulting measurements of one frame can be denoted by $\mathbf{X} \in \mathbb{C}^{M_r \times S \times A}$. Given $\mathbf{X}$, important parameters for the proposed scheduler, including the range and velocity of moving target(s) in the surroundings, are extracted. Once the IF signal is obtained by the correlation of the transmitted and received echo, the parameters are extracted through a range-Doppler matrix that is obtained by the 2D fast Fourier transform method over each coherent processing interval [26]. It should be noted that the investigation of this method is not given in our paper since it is out of the scope of the proposed MAC-based scheduler. After the radar information is extracted, they are fed into the communication module. In the following subsection, the communication model is described.

B. COMMUNICATION MODEL

The considered BS employs a mmWave OFDM-based transmitter with M_A antennas which is used to communicate with multiple single-antenna mobile users. Adopting a narrowband channel model with P paths, the channel between the k-th user and the BS can be expressed as [27]

$$\mathbf{h_k} = \sum_{p=0}^{P-1} \alpha_p \mathbf{a}\left(\phi_p, \theta_p\right), \quad (4)$$

where α_p denotes the complex gain, $\mathbf{a}\left(\phi_p, \theta_p\right)$ is the array response vector of the BS, and ϕ_p, θ_p represent transmit azimuth and elevation angles of the p-th path at BS. In the downlink, the BS transmits the data symbol s_d to the user via the beamforming vector $\mathbf{f} \in \mathbb{C}^{M_A}$. The receive signal at the k-th user can be written as

$$y_k = \sqrt{\mathcal{E}_c} \mathbf{h_k}^H \mathbf{f} s_d + n, \quad (5)$$

where $n \sim \mathcal{CN}\left(0, \sigma^2\right)$ is the additive white Gaussian noise (AWGN) with a variance of σ^2, and $\sqrt{\mathcal{E}_c}$ is the transmitter gain of the BS. The signal-to-noise ratio (SNR) measured at the k-th user can be written as

$$SNR_k = \frac{\mathcal{E}_c |\mathbf{h_k}^H \mathbf{f}| P_{s_d}}{\sigma^2}, \quad (6)$$

where $P_{s_d} = \mathbb{E}[|s_d|^2]$ is the average power of s_d. SINR quantity should be measured as a pertinent indicator of the system's merit due to the unwanted signal that is picked up from other interfering BSs. The SINR, expressed in dB, measured at the target user is calculated as the SNR received from the intended BS minus the sum of power received from all other concurrently active BSs.

In the conventional communication channel state information (CSI) acquisition process, a known pilot signal is transmitted, and the communication beams are adjusted based on this signal [28]. The FMCW radar signal being a known signal, is used in the considered system to estimate the CSI for the communication users rather than transmitting additional pilots. As a result, pilot transmission overhead is reduced [26]. Furthermore, the radar measurements are leveraged to optimize the communication scheduler's performance. Based on the classical SINR measurements and the information gathered about the users from the echo signal, namely range (g_k) and velocity (v_k), the BS allocates its available resources to the users. The next section contains more information on the proposed multi-user scheduling scheme.

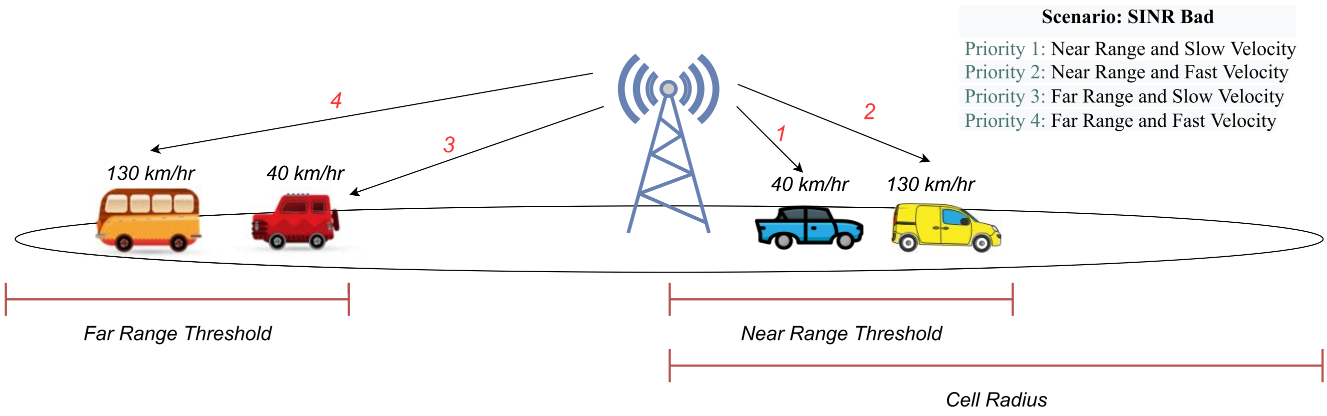

FIGURE 3. Scheduling priorities for bad SINR scenario.

III. PROPOSED SCHEME

A new scheduling algorithm is proposed in this paper based on the range, velocity, and SINR information collected from the radar echo signal reflected from a target. The positions and velocities of vehicles are estimated. With the assistance of the radar, it is much easier to detect and track the moving vehicles. As shown in the field measurements in [29], the accuracy of position information provided by radar is higher than that by the Global Positioning System (GPS), resulting in a larger reduction in communication overhead when leveraging position information provided by a radar sensor than when leveraging GPS-based position. Based on the considered scheduling inputs, we set the following scheduling rules:

- UEs near the BS are prioritized due to low path loss; UEs in the center of the cell have a better channel quality indicator (CQI) and modulation scheme than UEs on the cell edge due to their proximity to the BS.
- Low-speed UEs are also prioritized due to their invariant channel conditions.
- UEs with better SINR are also prioritized due to their high power.

Figure 3 shows the scheduling priorities for bad SINR scenario. Regarding the range parameter, the conventional relationship between signal strength and range in free space is that the power of radio signals decreases with the square of the distance (d). The SNR decreases with d due to path loss, so range knowledge can be utilized to estimate received power and interference level. It should be noted that SINR should be high to receive the packet correctly. For example, the minimum required SINR could be 0 dB.

The range and velocity of the target can be extracted from the echo signal. The radar receiver uses different signal detection algorithms, e.g. correlation-based methods [30]. Based on the considered coexistence communication and radar use cases, it is found that range and velocity are the critical metrics to be measured. Figure 4 shows the proposed radar-aided communication scheduler. We consider a DL transmission from BS to UE in a typical radar-aided communication system.

TABLE 2. Use cases proposed by Hexa-X [31] along with selected performance metrics, based on [32], [33], [34], [35] and [36] .

Use cases	Range	Velocity
Smart city	< 200m	< 50 km/h
Health care	0.1-10 m	< 1 m/s
Transport cobots	< 200 m	< 100 km/h
Industrial cobots	< 200 m	< 30 km/h
Public safety/security	< 200 m	< 50 km/h
Mixed reality, gaming	< 10 m	< 10 km/h

The scheduling inputs are collected by the echo signal from the target. These inputs include range, velocity, and SINR information. The considered inputs are imported from the considered applications and use cases. Some numerical values of the considered inputs can be shown in Table 2 [37]. It should be noted that the velocity metric, shown in Table 2, refers to the maximal (relative) velocity that should be supported.

Based on the considered scheduling inputs, we set proper scheduling rules. The range-based scheduling rule is set where UE near the BS is prioritized due to low path loss. The velocity-based scheduling rule is set where low-speed UEs are prioritized due to their invariant channel conditions. The SINR-based scheduling rule is set where UEs with better SINR are also prioritized due to their high power. We consider a scenario where multiple BSs and UEs exist in the communication network. In this case, SINR is measured since the interfering BSs cause interference to the desired UE served by its serving BS [38]. For simplicity, equal radar and communication transmit powers are assumed.

The estimated range and velocity from the considered system, as well as some of the assumptions made in the proposed scheme, are described further. Basically, the mutual distance between k-th UE and b-th BS, d_{bk} (km), can be found as [39]

$$d_{bk} = \sqrt{\left(m_{k,x_2} - m_{b,x_1}\right)^2 + \left(m_{k,y_2} - m_{b,y_1}\right)^2}, \tag{7}$$

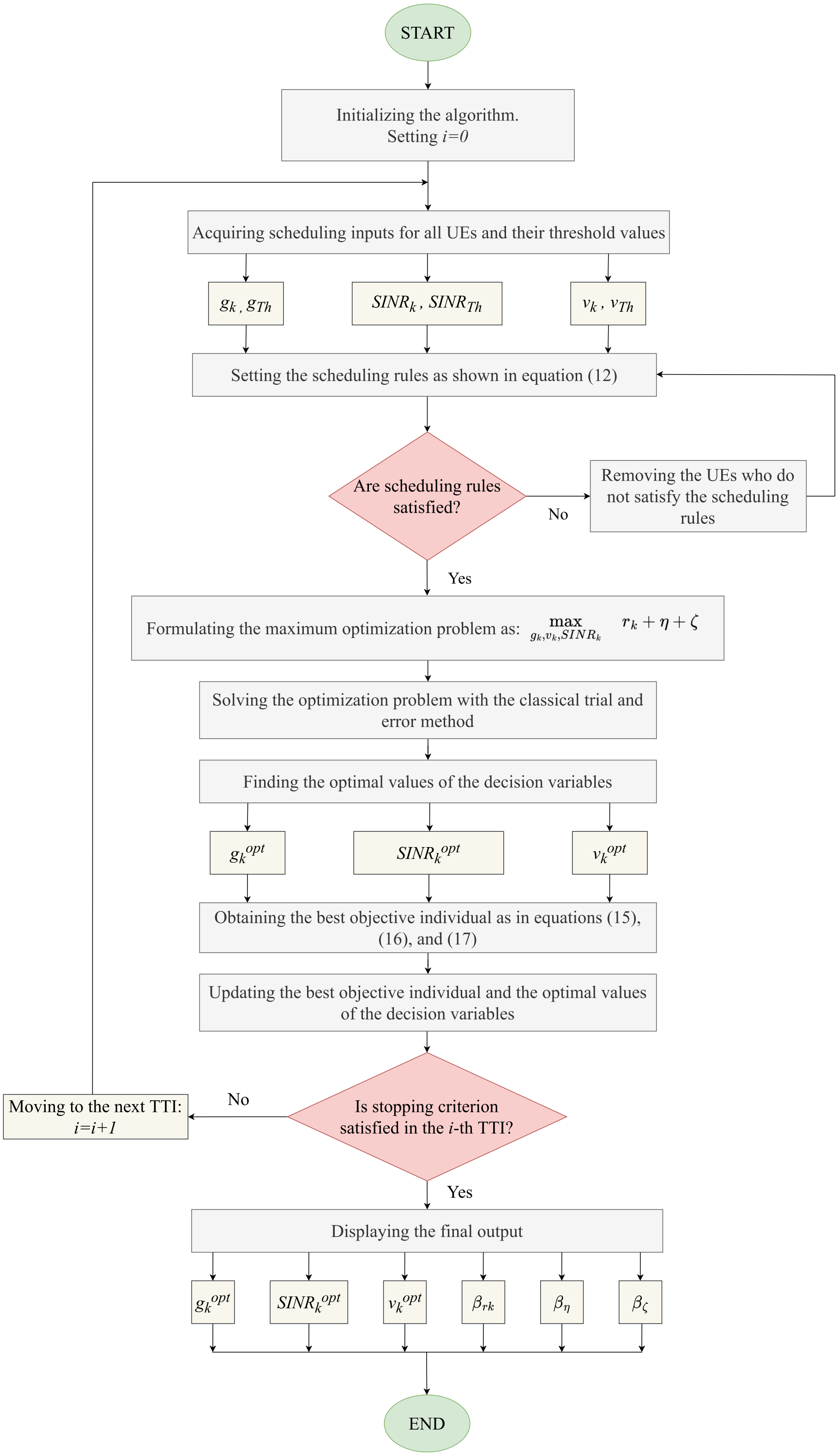

FIGURE 4. **The proposed scheduling algorithm.**

where m_{k,x_2} and m_{k,y_2} represent the position of k-th UE in the x and y axis, respectively, and m_{b,x_1}, m_{b,y_1} denote the position of b-th BS in the x and y axis, respectively. Then, the path loss (dB) can be calculated as [40]

$$PL_{bk} = 32.45 + 20\log_{10}(d_{bk}) + 20\log_{10}(f_c), \tag{8}$$

where f_c represents the carrier frequency in MHz. The received power (dB) can be represented as

$$P_{bk}^{Rx} = P_{bk}^{Tx} - PL_{bk}, \tag{9}$$

where P_{bk}^{Tx} (dB) represents the transmitted power from b-th BS to k-th UE. Then, the SNR (dB) can be evaluated as follows:

$$SNR_k = P_{bk}^{Rx} - BN_0, \tag{10}$$

where N_0 is the power spectral density (PSD) of AWGN, and B represents the system bandwidth. The quality of the radio link between b-th BS and k-th UE can be measured by considering the interference effects caused by interfering BSs as

$$SINR_k = SNR_k - \sum_{v \in \mathbb{V}} P_{vk}^{Rx}, \tag{11}$$

where $\mathbb{V}$ is the set of interfering BSs and P_{vk}^{Rx} (dB) is the interference power received from the v-th interfering BS.

The goal of the proposed approach is to schedule BS transmissions so that the range (g_k), velocity (v_k), and SINR ($SINR_k$) are higher than specific threshold values g_{Th}, v_{Th}, and $SINR_{Th}$ for every UE k that can receive a transmission from a scheduled BS:

$$\begin{aligned} g_k &\geq g_{Th} \\ v_k &\geq v_{Th} \\ SINR_k &\geq SINR_{Th}. \end{aligned} \tag{12}$$

According to the SINR formulated in (11), the data rate of k-th UE can be expressed as

$$r_k = B \log_2(SINR_k) \tag{13}$$

The domain knowledge offered by the considered system provides a high reduction in communication overhead to extract g_k and v_k fed to the communication modules, thus enhancing SE (η). Furthermore, the accuracy in estimating g_k and v_k is proportional to the system throughput (ζ). Our scheduler maximizes r_k, η, and ζ. The decision variables that control the considered scheduler outputs are g_k, v_k, and $SINR_k$. The formulation of the objective function is shown as

$$\begin{aligned} \max_{g_k, v_k, SINR_k} \quad & r_k + \eta + \zeta \\ \text{s.t. } & g_k \geq g_{Th} \\ & v_k \geq v_{Th} \\ & SINR_k \geq SINR_{Th} \end{aligned} \tag{14}$$

The values g_k^{opt}, v_k^{opt}, and $SINR_k^{opt}$ are optimally chosen using the classical trial and error method [41] to maximize the considered scheduling outputs. The employed trial and error method continues until the stopping criterion is satisfied. The selected values of the considered scheduler outputs correspond to the optimal factors at the i-th transmission time interval (TTI). Mathematically, the optimal solutions can be found as

$$\beta_{r_k} = \arg\max_i r_k^i \tag{15}$$

$$\beta_\eta = \arg\max_i \eta^i \tag{16}$$

$$\beta_\zeta = \arg\max_i \zeta^i \tag{17}$$

Algorithm 1 shows the step-by-step proposed radar-aided communication scheduling algorithm.

Algorithm 1 Radar-Aided Communication Scheduling Algorithm

Input: The scheduling inputs.
Output: The scheduling outputs.
While stop criterion is not satisfied in i-th *TTI*

A. Pre-Processing
 1: **Acquiring scheduling inputs for all UEs:** g_k, v_k, $SINR_k$.
 2: **Acquiring the threshold values for the scheduling inputs:** g_{Th}, v_{Th}, $SINR_{Th}$.
B. Setting the scheduling rules
 3: **Check** if $g_k \geq g_{Th}$.
 4: **Check** if $v_k \geq v_{Th}$.
 5: **Check** if $SINR_k \geq SINR_{Th}$.
 6: **Else**
 7: **Go to Step 1**
C. Forming the optimization problem
 8: **Find** $\max_{g_k, v_k, SINR_k} r_k + \eta + \zeta$.
D. Finding the final output
 9: **Find** g_k^{opt}, v_k^{opt}, and $SINR_k^{opt}$
 10: **Set** $\beta_{r_k} = \arg\max_i r_k^i$
 11: **Set** $\beta_\eta = \arg\max_i \eta^i$
 12: **Set** $\beta_\zeta = \arg\max_i \zeta^i$

End

IV. RESULTS AND DISCUSSION

The performance of the proposed approach is evaluated using system level simulation (SLS), then the key performance indicators (KPIs) are investigated.

A. SIMULATION SETUP

Figure 5 shows the considered multi-cell scenario where the cellular topology is adopted in a single ring hexagonal structure with 7 5G BSs (gNBs), and their positions are at the center of the hexagonal cell in a square area. Users are dropped in the same area according to a uniform spatial distribution across the region of interest (ROI), which is around 7×7 km in size.

We focus on downlink transmissions without power control, as is the case in the majority of state-of-art proposals. It is assumed that BS knows the DL traffic demands that are cached in its buffer. UEs are associated to BSs based on the strongest average received power, i.e., based on distance, and do not change BS during the simulation. Fading is considered in the numerical simulations in addition to path loss, through a random variable, expressed in dB, distributed as a zero-mean Gaussian with a variance of σ^2 [42].

TABLE 3. System parameters.

Parameters/Symbols	Values/Description
Transmission bandwidth (B)	5 MHz
Carrier frequency (f_c)	5 GHz
BS transmit power (P_b^{Tx})	46 dBm
Noise PSD (N_0)	-174 dBm/Hz
Cell radius (R_c)	1400 m
Inter-site distance ($d_{k,v}$)	2425 m
Number of BSs (N_{BS})	7
Number of UEs per BSs (N_{UE-BS})	10
Total number of UEs (N_{UE})	70
Schedulers	RR, BCQI, PF
Number of available RBs (N_{rb})	15
Number of subchannels in a RB (N_c)	12
Number of available slots for scheduling (N_s)	20
Slot duration (T_s)	0.5 ms
Subchannel bandwidth (B_s)	180 kHz
Number of symbols in a RB (N_b)	7
BS configuration	Omni-directional
Transmission time interval (TTI)	2 ms
Number of Monte-Carlo Runs (N)	1000

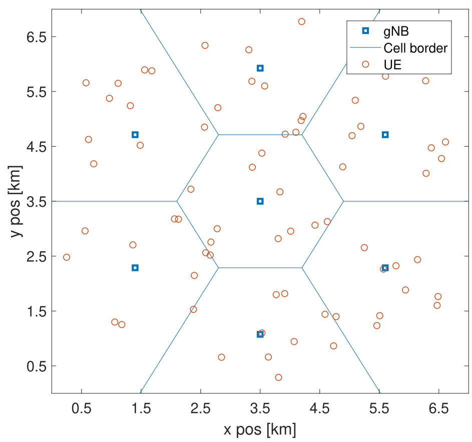

FIGURE 5. Simulation network layout.

The proposed scheduler selects the UE to transmit in each time slot. As a basic scenario, perfect CSI is assumed to be available at the start of each time slot for schedulers and that at most one UE is allowed to transmit in each slot. The parameter specifications for the number of slots (N_s), slot duration (T_s), subchannel bandwidth (B_s), TTI, etc. can be found in Table 3. The considered scheduling inputs are imported from Table 2.

B. SIMULATION METRICS

To understand the functioning of the proposed approach in much more detail, its performance is evaluated by considering the RR, PF, and BCQI methods in terms of average data rate (bits/s), throughput (bits/s), and SE (bits/s/Hz) over 1000 different channel realizations [43].

The average system and UE data rate, system throughput, and SE are found as follows, respectively:

$$\overline{r} = \frac{N_i}{N_{rb}N_cN_bT_sN_s} \tag{18}$$

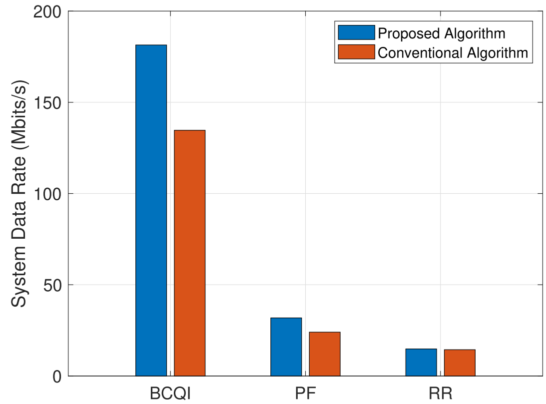

FIGURE 6. System data rate of the proposed scheduler compared to the conventional one.

$$\overline{r_k} = \frac{N_i}{N_{UE}N_sT_s} \tag{19}$$

$$\overline{\zeta} = \frac{N_i}{N_sT_s} \tag{20}$$

$$\overline{\eta} = \frac{N_i}{N_s\ TTI\ N_{rb}B_s} \tag{21}$$

where N_{UE}, N_i, N_{rb}, N_b, and N_c represent the total number of UEs, number of correctly received bits, number of available RBs, number of symbols in an RB, and number of subchannels in an RB, respectively.

C. STATE-OF-ART SCHEDULING ALGORITHMS

The most commonly used scheduling methods are PF, BCQI, and RR in the literature and practice [44]. The available RBs are distributed using the PF, BCQI, and RR. The performances of PF, RR, and BCQI are analyzed under the proposed approach. For the same simulation scenario, the three scheduling techniques are used.

The PF method is one of the most widely used methods for fair scheduling [23], aiming to provide fairness while taking advantage of good channel conditions and dynamically allocating resources to UEs. It is proven in [45] that the PF is not optimal due to capacity constraints. The RR method provides RBs for UEs without considering channel conditions; this is a simple procedure that ensures fairness [46]. The BCQI method is a common channel-dependent scheduler. The channel variations between UEs are exploited in this scheduler to maximize cell throughput at the expense of fairness [47].

D. SIMULATION RESULTS

Here, the simulation results are presented along with their discussions. MATLAB-based SLS is used to evaluate the performance of the proposed approach. The achieved results are shown with the classical methods, i.e., PF, RR, and BCQI. During the simulations, the default parameters are listed in Table 3. The simulation results here showed the realistic case in which the signal experiences interference and noise simultaneously. Because of that, the SINR of UE has been measured when the power of the noise term is zero. Then,

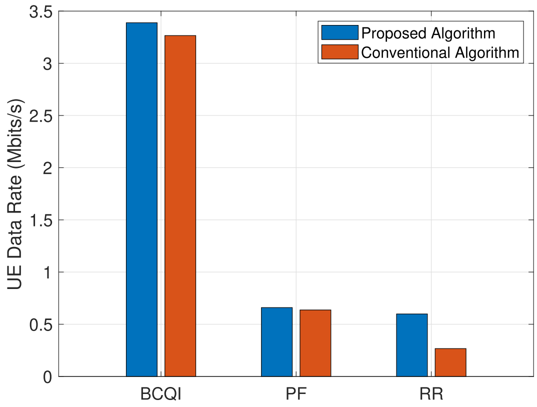

FIGURE 7. UE data rate of the proposed scheduler compared to the conventional one.

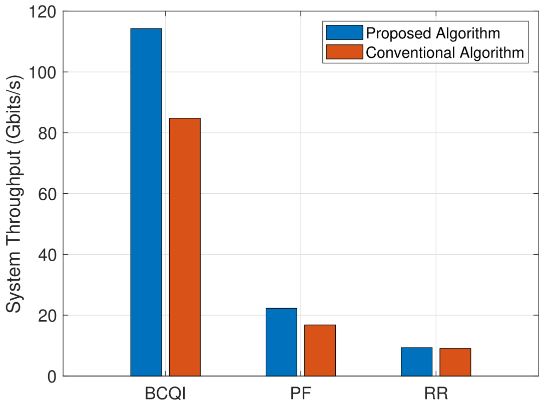

FIGURE 8. System throughput of the proposed scheduler compared to the conventional one.

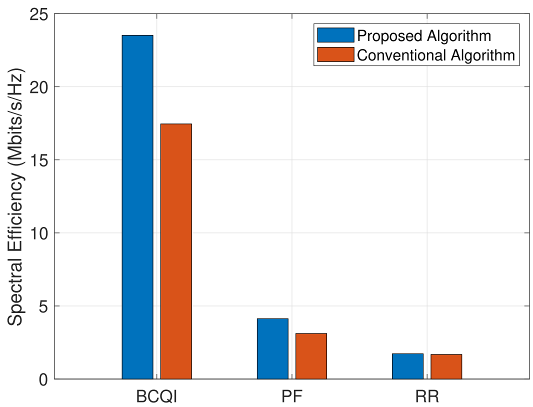

FIGURE 9. SE of the proposed scheduler compared to the conventional one.

the SINR reduces to the signal to interference ratio (SIR). Conversely, zero interference reduces the SINR to the SNR.

Figures 6, 7, 8, and 9 show the performance of the proposed scheduler compared to the conventional one in terms of data rate, system throughput, and SE considering 15 available RBs. The achieved results show that the proposed scheduler, considering SINR, range, and velocity as inputs to the scheduler, is better than the conventional scheduler where SINR is only considered. It is demonstrated that the BCQI outperforms the PF and RR in terms of data rate, SE, and system throughput under the proposed scheme. The reason behind this is the channel-dependent characteristics of BCQI while assigning RBs, resulting in superior spectrum utilization. The results also show that the performance of the PF is slightly better than the RR. The RR performs the worst because it reduces throughput, data rate, and SE. On another side, it offers greater resource allocation fairness among different UEs. It is worth noting that the throughput depends on the simulated channel state, which influences the achievable transmission rate and the UE scheduling mechanism adopted by BS.

V. CONCLUSION

More effective scheduling algorithms are required to fulfill the needs of new applications such as radar and communication coexistence. We propose a new radar-aided scheduling algorithm in a practical vehicular communication scenario by utilizing some parameters, including range, velocity, and the conventional SINR measurements. The fundamental idea is to create the communication scheduler at the BS using the estimation of the scheduling inputs derived from the radar echo signal. The proposed scheme introduces a new degree of freedom to the scheduling design in radar-aided communication systems that leads to an efficient scheduling algorithm. The proposed scheme is evaluated in terms of data rate, UE and system throughput, and SE. The simulation results prove that the proposed scheduler outperformed the conventional one. Moreover, the obtained results show a significant performance of the proposed scheduler using the BCQI over the PF and RR. The results show that radar can be a valuable source of side information for the communication scheduler over a mmWave V2I link. The proposed algorithm should be viewed as a preliminary solution to demonstrate the approach's practicality, although it can be modified further. As future work, the optimal solutions could be further improved by employing more efficient optimization methods than the adopted trial and error method. Furthermore, the scheduling rules can be extended by incorporating the angular parameter from the radar echo to enhance the performance of the scheduler.

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