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RESEARCH ARTICLE

Adaptive C-RAN Architecture Using Crowdsourced Radio Units for Smart City

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ABSTRACT This paper proposes a concept of adaptive centralized radio access network (C-RAN) architecture for a smart city using crowdsourced radio units (CRUs). To efficiently manage the ever-increasing mobile traffic, mobile networks have improved their capacity. The C-RAN architecture with the dense deployment of small cells has become prevalent in today's mobile networks. However, the spatiotemporal fluctuation in traffic demand deteriorates the cost and operation efficiencies of conventional networks. Such fluctuation is expected to be intensified in the future in accordance with the increase in the data rate. To address this problem, the proposed architecture utilizes the power of citizens in the network deployment by employing the concept of vehicle-mounted small cells. The onboard CRUs are activated by edge servers when vehicles move to high-demand areas and deactivated when they move to low-demand areas. This paper also proposes the activation algorithm executed by edge servers based on the traffic information measured by roadside units (RSUs). Computer simulations demonstrate that the proposed scheme can improve network throughput during both daytime and nighttime. The proposed architecture contributes to the efficient deployment of mobile networks and better energy use in a smart city.

INDEX TERMS C-RAN, mobile networks, crowdsource, vehicular networks.

I. INTRODUCTION

The prevalent architecture in modern mobile networks, such as 5G and beyond, is the Centralized Radio Access Network (C-RAN) which efficiently handles the continually increasing traffic [1]. By deploying a large number of small cells alongside macro cells, the network capacity is enhanced thanks to the improved spectrum efficiency brought about by reducing the cell size. The C-RAN architecture is comprised of three main components, as depicted in Figure 1 [2]: a central unit (CU), a distributed unit (DU), and a radio unit (RU). The CU pool is typically located in a central office, and the link connecting the CU and DU is referred to as midhaul. Small cells are created by densely deploying multiple RUs, and the link connecting a DU and an RU is known as fronthaul.

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Due to the strict latency requirement of fronthaul, which must be $\leq$ 100 μs [3], DUs are situated in close proximity to RUs. Fronthaul networking has become a popular research topic for efficient deployment of C-RAN, with many studies exploring the use of passive optical networks (PON) [4], [5] and bridged networks [6], [7]. Additionally, the optimization of fronthaul deployment through the use of wireless links has been proposed as a means of efficiently deploying numerous RUs [8].

Metropolitan areas generally experience significant fluctuations in mobile traffic demand [9], [10]. This trend is caused by various population movements, such as commuting, resulting in a greater number of mobile phone users in office areas during the daytime than at night. With the increase in mobile network data rates, these fluctuations are expected to intensify in the future, which can lead to a significant decrease in the efficiency and financial viability of conventional mobile networks. The reason for this is that base stations (BSs) have been deployed to handle peak rates in each area, and their capacities are underutilized for most of the time. To address this issue, an adaptive network architecture has been proposed to adjust to fluctuations in mobile traffic [11]. In this proposed architecture, mobile BSs follow changes in demand distribution to forward mobile traffic. Additionally, the concept of an optically backhauled moving network for local trains was proposed in [12] and [13] as a deployment scenario for this adaptive network architecture.

A more recent proposal for deploying mobile networks is the concept of vehicle-mounted small cells, which aims to leverage the power of citizens [14]. In this architecture, onboard RUs are used to create small cells and relay uplink/downlink traffic between DUs and user equipment (UE). Based on the current incentive value and power consumption, the driver has the ability to activate or deactivate small cell functions. The incentive value is established by the network operator, taking into account factors such as traffic demand and the number of onboard RUs in each area. Vehicle-to-pedestrian (V2P) connectivity at higher frequency bands was analyzed in [15] to evaluate the effectiveness of this network architecture.

This paper delves further into the concept of utilizing crowdsourced RUs (CRUs) for efficient deployment of mobile networks. The proposed approach in this paper suggests an adaptive C-RAN architecture for a smart city, using CRUs and multi-access edge computing (MEC). The primary contribution of this work is the optimal control of vehicle-mounted CRUs by edge servers, based on the distribution of CRUs and road traffic measured by roadside units (RSUs). In contrast, the vehicle-mounted small cells proposed in [14] were managed by drivers. While the idea was introduced in [16], the activation algorithm was simplistic for moving vehicles, and the performance evaluation was insufficient. Therefore, this paper proposes a sophisticated activation algorithm and provides a thorough performance evaluation of wireless fronthaul links through computer simulations.

The rest of the paper is organized as follows. Section II describes the related work. Section III introduces the proposed network architecture. Section IV describes the results of performance evaluation via numerical analysis. The simulation results for wireless fronthaul links are provided in Section V. The conclusion is provided in section VI.

II. RELATED WORKS

A. MOVING SMALL CELL

The concept of moving small cells has been investigated to efficiently deploy small cells in C-RAN. In [17], the performance of moving cells was evaluated in the scenario where they were mounted on public buses. The moving cells aggregate user traffic and communicate with macro cells via wireless backhaul links. It was supposed in [18] that small cells are deployed on top of public transportation vehicles such as buses and taxis. The vehicle-mounted cells move

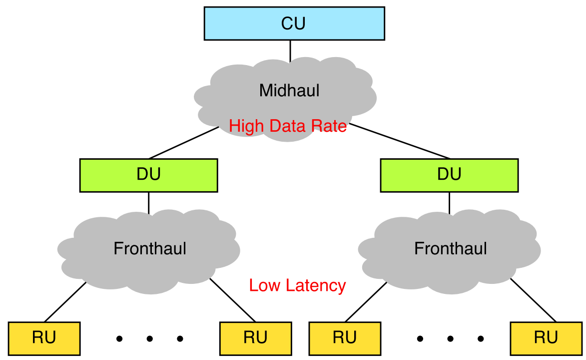

FIGURE 1. C-RAN architecture.

around crowded streets and carry traffic generated by the passengers and their vicinities. It was indicated that the proposed scheme was efficient in crowded areas in the presence of stationary traffic hotspots inside macro cells. A joint allocation problem of resource blocks and power was proposed in [19] to enhance the quality-of-service (QoS) in cellular networks with moving small cells. A vehicular communications system that achieves multi-Gbps data rate transmission for train and car applications was proposed in [20] to provide mobile backhaul connectivity for vehicle UEs. It employs a relaying network architecture to support a high data rate with a high carrier frequency while guaranteeing sufficient robustness against high mobility-related behaviors such as fast channel variation and unstable handover. The defined problem aims to efficiently allocate resources in moving environments that create time-varying interference. However, the major goal of these schemes is to provide connectivity for passengers in moving enclosed vehicles.

B. VEHICULAR COMMUNICATIONS SYSTEMS

Vehicular communications systems have attracted considerable attention in recent years. An idea of vehicle-to-vehicle (V2V) communications via mobile networks was presented in [21]. They also proposed a resource allocation scheme that decreases the interference between vehicular nodes and normal cellular users. Millimeter-wave (mmWave) communications is a major option for V2V and vehicle-to-infrastructure applications, where vehicles are being equipped with numerous sensors generating even higher data rates [22]. The authors of [23] proposed a highway communications model where vehicles are served by mmWave BSs deployed alongside the road. They considered a theoretical model for a typical scenario where heavy vehicles, including buses and lorries, obstruct the line-of-sight paths of other vehicles.

It was pointed out that the security and protection of users' privacy are significant issues in vehicular communications systems [24]. To ensure the security for communications links, two physical layers (PHY) security techniques for vehicular mmWave communications systems were proposed in [25]. They employed multiple antennas with a single radio-frequency (RF) chain and a few RF chains to transmit information symbols to a target receiver. A vehicular public-key infrastructure (VPKI) system compatible with the IEEE 1609.2 and ETSI standards specifications were introduced in [26].

However, the research on vehicular communications systems has yet to consider the use case where vehicles provide network connectivity for mobile users around them.

C. VEHICLE-MOUNTED CELL

The concept of vehicle-mounted small cells was proposed to dynamically deploy small cells dealing with fluctuating demand [14], [15]. The proposal in [14] utilizes the power of citizens in deploying mobile networks. With this architecture, an onboard RU is mounted on a vehicle and establishes a wireless fronthaul link with a ground DU to serve as a small cell. A vehicle-mounted small cell relay uplink and downlink traffic of UEs around it. This work assumed that the vehicle's driver turns on or off the mounted RU based on the current incentive value given by the network operator. To this end, they proposed a method for calculating the incentive value considering the situation in each area, e.g., traffic demand and the number of onboard RUs.

To ensure the possibility of vehicle-mounted small cells, the performance of V2P connectivity with a higher frequency band such as 28 GHz was evaluated in [15]. It was confirmed through computer simulations that multiple cells could be utilized for a coordinated multipoint (CoMP) transmission/reception to expanding coverage.

However, it is difficult to optimally control the states of onboard RUs by fully counting on drivers' decision-making. Therefore, this paper proposed a novel concept of adaptive C-RAN architecture for a smart city using CRUs based on the idea presented in these works. The contribution of this work is to propose a scheme for optimally controlling the states of onboard CRUs based on their distribution and road traffic measured by RSUs.

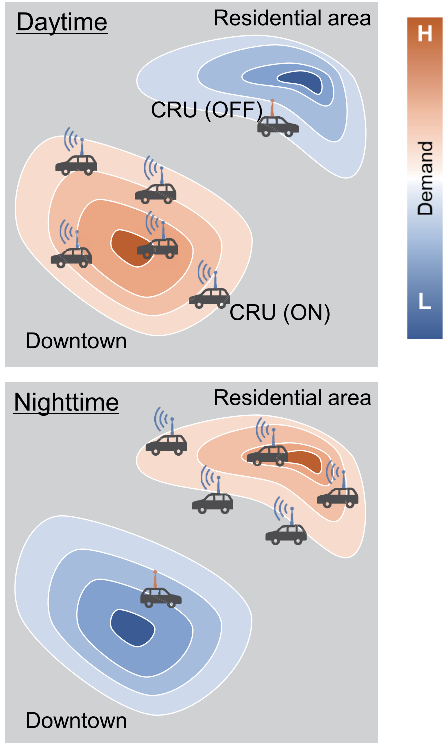

FIGURE 2. Demand and CRU distribution.

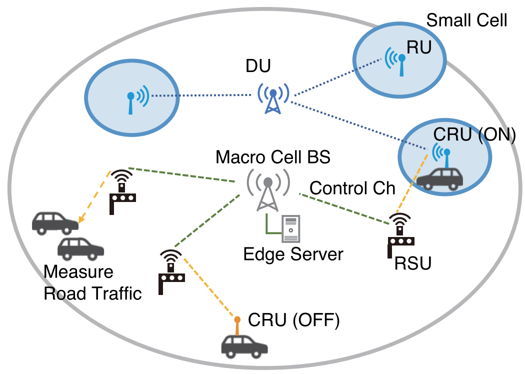

FIGURE 3. Conceptual system architecture.

III. PROPOSED NETWORK ARCHITECTURE

A. CONCEPT

Fig. 2 illustrates the fundamental concept behind the proposed network architecture. CRUs are equipped in various types of vehicles such as taxis, private cars, buses, and trucks. These units are activated by an edge server when mobile users enter an area with high mobile traffic demand and deactivated when they leave. When a CRU is activated, it serves as a small cell and establishes a wireless fronthaul link to a nearby DU to relay uplink/downlink traffic between DUs and UEs. This architecture offers high flexibility and low cost, as the distribution of vehicles in a city often reflects human mobility patterns, which means more vehicles are present in crowded areas.

As shown in Fig. 3, the activated CRUs on-board the vehicles are connected to DUs via wireless fronthaul links. These CRUs provide small moving cells over static small cells composed of ground RUs. The power of CRU is sourced by the vehicle battery that produces surplus power while in motion; the proposed framework can improve energy utilization efficiency. The proposed architecture assumes the widespread deployment of RSUs in the city, as a part of enabling various vehicle-to-vehicle communications or intelligent transportation systems. RSUs measure the distribution of CRUs and road traffic in their surrounding areas. In addition, the architecture employs an edge computing scheme, wherein an edge server is installed with a macro cell BS and creates a logical control channel with RSUs through the macro cell connections. The edge server computes the optimum state of CRUs and activates/deactivates them via RSUs.

B. ACTIVATION SEQUENCE

The flow in Fig. 4 illustrates the process of activating CRUs. In order to determine the distribution of demand in a given

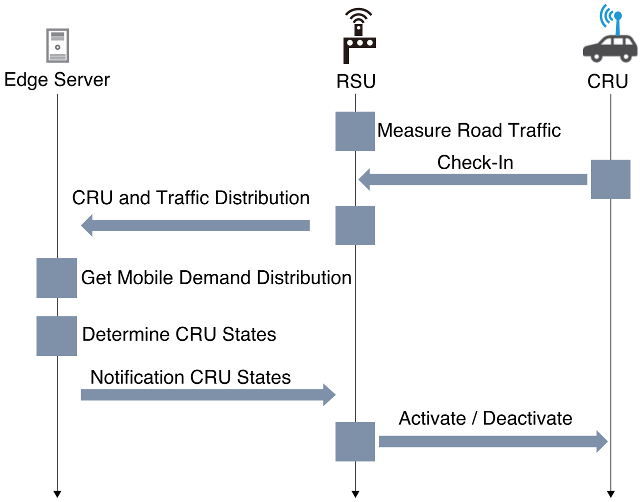

FIGURE 4. Activation sequence.

area, an RSU takes regular measurements of the surrounding road traffic. When a CRU enters the coverage area of an RSU, it establishes communications with the RSU using a wireless protocol like Bluetooth low energy (BLE). The CRU registers with the RSU and shares information such as its current battery level. The RSU logs the check-in time and the CRU sends periodic keep-alive messages while it is within the communications area. When the CRU moves out of the cover area, it checks out automatically. Alternatively, if the RSU fails receiving keep-alive messages, the CRU is checked out automatically.

The RSU periodically transmits the information it has collected to the edge server through a macro cell link. The received road traffic data is used by the edge server to update the mobile demand distribution. If provided by the mobile network operators, the current mobile load and user information can be incorporated into the process. The edge server then uses this information to compute the status of CRUs and sends the results to the RSUs. Based on the received information, the RSU activates or deactivates the CRUs that have been checked in. Once activated, a CRU sets up a fronthaul link with a neighboring DU and begins forwarding mobile traffic.

C. ACTIVATION ALGORITHM

1) VARIABLES

The variables used in the proposed algorithm are summarized in Table 1. Let r denote the identifier for RSUs and their coverage areas. d_r stands for the mobile traffic demand in the r-th area. Let $\mathcal{C}_r$ and c denote the set of CRUs in the r-th area and the identifier for them, respectively. t_c indicates the check-in time of the c-th CRU. c-th CRU is assumed to be able to accommodate s_c of demand, which is determined by its performance of it, including the current battery level. If the current battery level is low for activating the CRU function, $s_c = 0$. $\mathcal{X}_r = \{x_1, x_2, \cdots x_c, \cdots\}$ is defined where x_c is a binary variable that represents the state of the c-th CRU; $x_c = 1$ is satisfied if it is activated, and otherwise $x_c = 0$.

TABLE 1. Variables used in activation algorithm.

Variable	Definition
r	Identifier for RSU and cover area
d_r	Mobile traffic demand in r-th area
$\mathcal{C}_r$	Set of CRUs in r-th area
c	Identifier for CRUs, $c \in \mathcal{C}_r$
t_c	Check-in time of c-th CRU
s_c	Capacity of c-th CRU
x_c	Binary variable for state of c-th CRU

With the defined variables, the requirement for demand satisfaction in r-th cover area is formulated as

$$\sum_{c \in \mathcal{C}_r} s_c x_c \geq d_r. \tag{1}$$

D. ALGORITHM

The following part elaborates on the method utilized by the edge server to determine the CRU states. This algorithm is implemented for every coverage area of the RSUs, ensuring its scalability.

The set of CRUs in r-th area, $\mathcal{C}_r$, change with time as vehicles on which CRUs are mounted move to their destination. The purpose of the proposed algorithm is to activate CRUs always to satisfy the mobile demand efficiently. To this end, the proposed algorithm is executed whenever an activated CRU checks out. The CRUs to activate are selected based on their check-in time because the newly added CRUs in $\mathcal{C}_r$ are expected to stay longer in the area.

The detailed procedure is explained in Algorithm 1. It requires $\mathcal{C}_r$ and $\mathcal{X}_r$, and ensures $\mathcal{X}_r'$ which denotes updated $\mathcal{X}_r$. First, $\mathcal{C}_r$ is sorted in descending order by the check-in time. Then, CRUs to activate are selected from $\mathcal{C}_r$ to satisfy the mobile demand as formulated in (1). If the demand is successfully satisfied, the activation procedure finishes with updated $\mathcal{X}_r'$. If there are not enough number of CRUs in the area to satisfy the demand, the activation algorithm ends with an error. To reduce the error rate, the proposed scheme should be employed under certain conditions, which is clarified in Section IV.

IV. NUMERICAL ANALYSIS

In order to clarify the applicability of the proposed network architecture, this section describes the results of the numerical analysis.

A. AREA DEMAND SATISFACTION

The variables used in the numerical analysis are summarized in Table 2. Let T_r denote the amount of road traffic in r-th area. It is assumed that T_r is formulated as

$$T_r = \alpha k d_r, \tag{2}$$

Algorithm 1 CRU Activation Algorithm

Require: $\mathcal{C}_r$, $\mathcal{X}_r$
Ensure: $\mathcal{X}'_r$

```
Sort By Check-in Time (C_r)
c ← 0
while Σ_c s_c x_c < d_r do
    if x_c = 0 & s_c > 0 then
        x_c ← 1
    end if
    c ← c + 1
    if c > |C_r| − 1 then
        Return (−1)
    end if
end while
Return(0)
```

TABLE 2. Variables used in numerical analysis.

Variable	Definition
α	Correlation parameter
β	Attach ratio of CRU
k	Weight
T_r	Road traffic in r-th area
v	Current battery level
a	Battery parameter

where k and α $(0 < \alpha \leq 1)$ respectively represent the weight and the correlation parameter that relates the road traffic to the mobile demand. When β $(0 < \beta \leq 1)$ denotes the attached ratio of CRU on vehicles, the size of $\mathcal{C}_r$ can be expressed as

$$\begin{aligned} |\mathcal{C}_r| &= \beta T_r \\ &= \alpha\beta k d_r. \end{aligned} \tag{3}$$

The value of capacity s_c is assumed to be determined as a sigmoid function using the current battery level v:

$$s_c(v) = \frac{1}{1+e^{-av}}, \tag{4}$$

where a is a slope coefficient for the battery level. Please note that d_r is expressed as a ratio with respect to the value of $s_c(\infty)$. In this paper, we assume that a is sufficiently large, meaning that the state of a CRU is either activated or deactivated. Additionally, we assume that v is normally distributed, resulting in $s_c(v)$ being either 0 or 1 with equal probability of 50%. Therefore, the number of available CRUs is half of the total number of $\mathcal{C}r$. Let $\mathcal{C}'r$ represent the set of available CRUs in the r-th area, which satisfies $2|\mathcal{C}'r| = |\mathcal{C}r|$. Considering only $c' \in \mathcal{C}'_r$, (1) is redefined as

$$\sum_{c' \in \mathcal{C}'_r} x_{c'} \geq d_r. \tag{5}$$

As a result, the minimum number of activated CRUs in the r-th area is equivalent to d_r. To fulfill this requirement, it is necessary that $|\mathcal{C}'r| \geq dr$. From equation (3) and the relationship $2|\mathcal{C}'r| = |\mathcal{C}r|$, the values of α and β must satisfy following condition

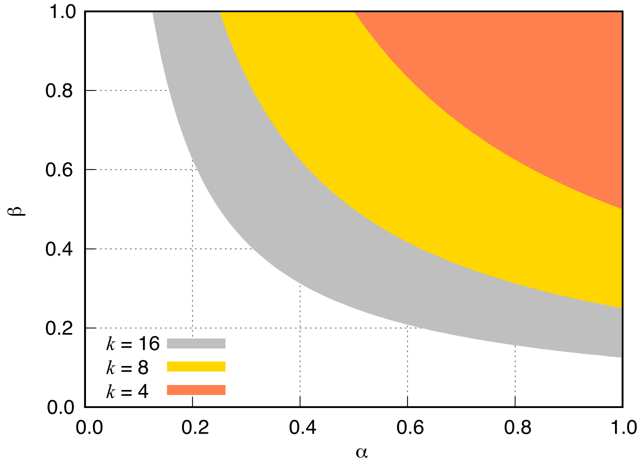

FIGURE 5. Requirement for α and β.

$$\alpha\beta \geq \frac{2}{k}, \tag{6}$$

which is represented by the shaded region in Fig. 5. Fig. 5 demonstrates that the stringency of the requirement is determined by the weight k, and that the attach ratio of CRU β can be low when the correlation α becomes higher. The minimum value of β is $\beta_{min} = \frac{2}{\alpha k}$. The reason why equation (5) does not depend on the demand d_r is due to the assumption of a correlation between road traffic and mobile demand.

B. MULTI-AREA DEMAND SATISFACTION

We define $\mathcal{R}$ as the set of areas within a target region that encompass both commercial and residential spaces. It is assumed that there is daily commuting between these areas; a change in the distribution of vehicles and mobile demand over time, while the total number of vehicles in the region remains constant. The mobile demand within the r-th area at time t is expressed as $d_r(t)$.

When $\beta_{min} = \frac{2}{\alpha k}$ is employed, the number of deployed CRU in r-th area is described as $|\mathcal{C}_r| = 2\, d_r(t)$ from (3). The total number of CRU in the target region is

$$|\mathcal{C}_\mathcal{R}| = 2 \sum_{r \in \mathcal{R}} d_r(t). \tag{7}$$

With the conventional ground RU deployment, the required number of ground RUs in r-th area g_r is equal to d_r^{max}, which is the maximum value of $d_r(t)$. Thus, the total number of ground RUs in the target region is

$$g_\mathcal{R} = \sum_{r \in \mathcal{R}} d_r^{max}. \tag{8}$$

Therefore, the cost ratio of the proposed CRUs and ground RUs is

$$\frac{|\mathcal{C}_\mathcal{R}|}{g_\mathcal{R}} = 2\frac{\sum_{r\in\mathcal{R}} d_r(t)}{\sum_{r\in\mathcal{R}} d_r^{max}}, \tag{9}$$

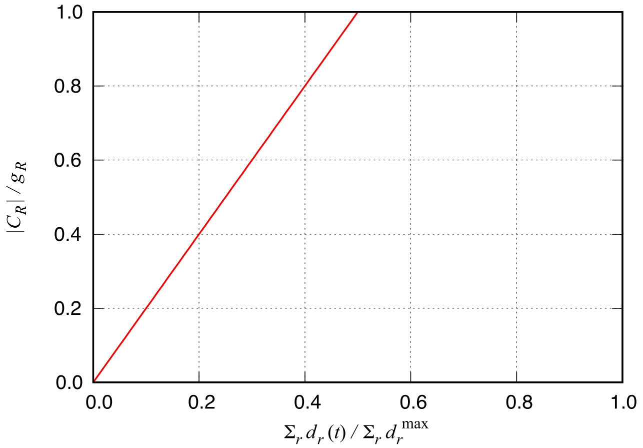

FIGURE 6. Cost ratio.

TABLE 3. Simulation conditions.

Variable	Values
Area size	10 km × 10 km
No. of UEs, N_U	2000, 10000
Center frequency	4.5 GHz
Signal bandwidth, B	100 MHz
Transmission power	33 dBm
Radio propagation model	3D-UMi NLOS [27]
Noise power	−85 dBm

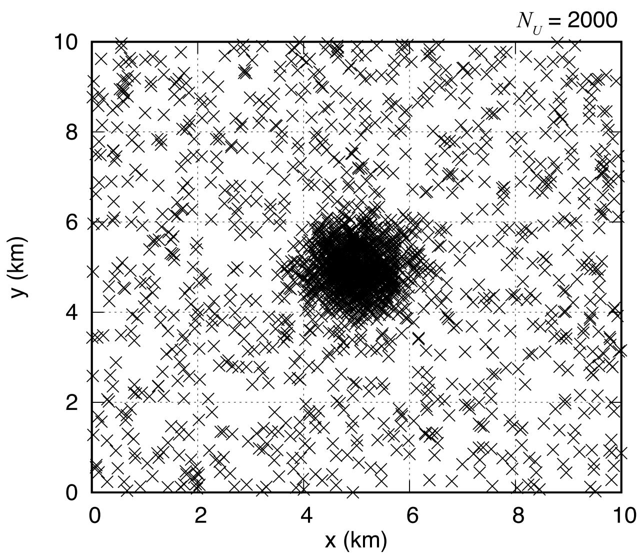

FIGURE 7. Example of UE distribution.

which is depicted in Fig. 6. This result implies that the proposed architecture is advantageous as the spatiotemporal fluctuation of mobile traffic demand is intensified.

V. COMPUTER SIMULATION

A. SIMULATION CONDITION

Tabletbl:condition lists the simulation parameters. UEs and CRUs are assumed to exist in a square area of 10 km. The

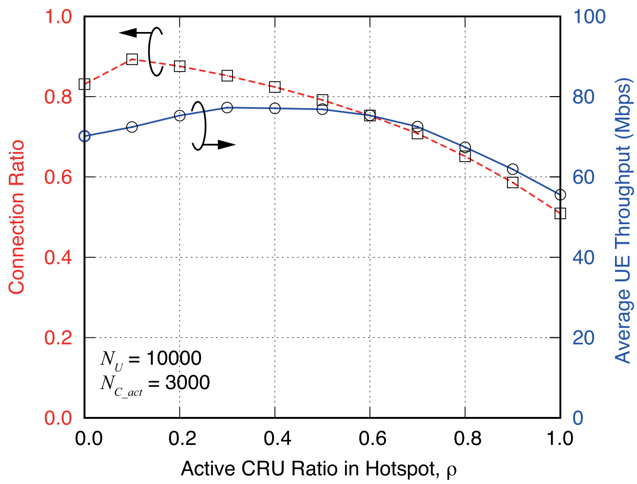

FIGURE 8. Connection ratio to active CRUs and average UE throughput characteristics at $N_U = 10000$ and $N_{C\_act} = 3000$.

number of UEs, N_U, was set to 2000 and 10000, assuming a difference in the UE distribution between nighttime and daytime. Fig. 7 shows an example of the UEs distribution. Half of the UEs were concentrated in the center of the area with a normal distribution with a standard deviation of 0.5 km, and the other half were uniformly distributed within the area. CRUs are assumed to be uniformly distributed within the area, and CRUs to be activated are selected from among them at random. The number of active CRUs is N_{C_act}, and ρ (≤ 1) is the ratio of active CRUs in the hotspot. In other words, the number of active CRUs in the hotspot is ρN_{C_act}. Therefore, active CRUs are also normally distributed.

When the available signal bandwidth is $B = 100$ MHz, the throughput of the u-th UE connected to the c-th active CRU is

$$R_u = \frac{B}{N_c} \log_2(1 + \gamma_u), \tag{10}$$

where N_c is the number of UEs connected to the c-th active CRU and γ_u is the SINR of the u-th UE. Note that the bandwidth B is used only for the link between the CRUs and the UEs; another bandwidth is used for the link above the CRUs or between the macrocell and the UEs. The UE was assumed to be able to receive signals from CRUs whose received power was greater than or equal to the noise power. The interference power is the sum of signals received from other than the active CRU to which the UE is connected. The UE is assumed to be fully buffered. Note that each UE can obtain throughput R_u by connecting to an active CRU. When there are no active CRUs to be connected, UE attempts to connect to a macrocell, and the throughput obtained by the macrocell is not considered in this simulation.

B. SIMULATION RESULTS: DAYTIME

First, let us consider the daytime when there are many UEs in the area. The number of UEs was set to $N_U = 10000$. When the number of active CRUs in the area was $N_{C\_act} = 3000$,

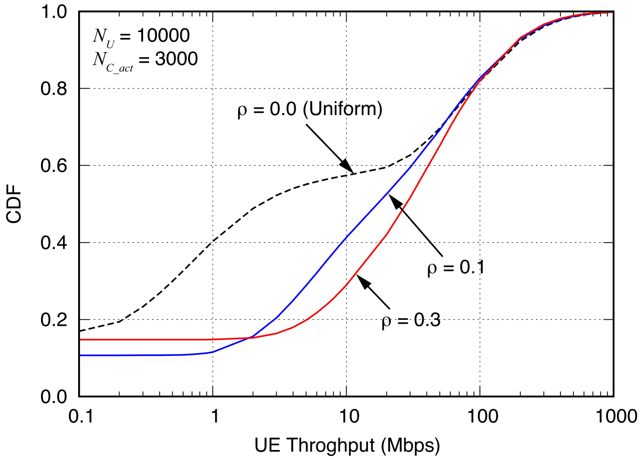

FIGURE 9. CDF characteristics of UE throughput at $N_U = 10000$ and $N_{C\_act} = 3000$.

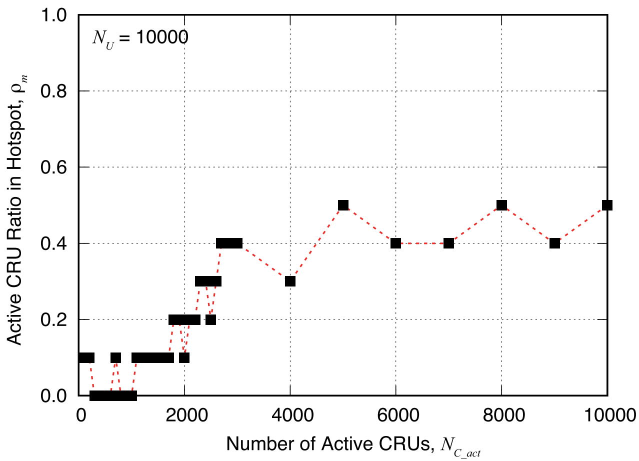

FIGURE 10. Active CRU ratio in hotspot areas with the number of active CRS when average UE throughput is maximized.

the connection ratio that UEs connect to active CRUs and the average UE throughput for ρ are shown in Fig. 8. Here, $\rho = 0.0$ means that active CRUs are uniformly distributed in the area. Setting $\rho = 0.1$ maximizes the connection ratio of UEs. On the other hand, setting $\rho = 0.3$ maximizes the average UE throughput, although the connection rate is reduced by about 10% compared to $\rho = 0.1$. This is because deploying more active CRUs in the hotspot can satisfy more UEs' communications demand in that area. Fig. 9 shows the cumulative distribution function (CDF) characteristics of UE throughput when $\rho = 0.0, 0.1, 0.3$. All the results show almost the same characteristics in the range of 100 Mbps and above. In the below 100 Mbps region, $\rho = 0.0$, the active CRUs are uniformly distributed so that UEs access in the hotspot are concentrated in the active CRUs; the ratio of UEs with low throughput increases. On the other hand, setting $\rho = 0.3$ can mitigate the demand load by deploying active CRUs at the hotspot, and hence UE throughput can be improved.

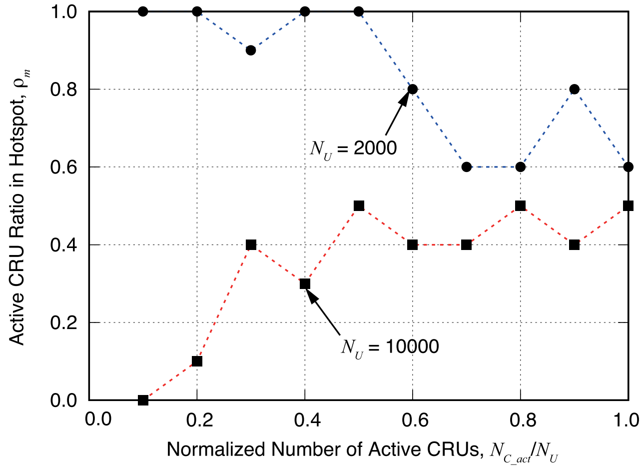

FIGURE 11. Active CRU ratio in hotspot areas with the normalized number of active CRUs.

Since this paper aims to satisfy the communications demand at the hotspot, the emphasis is on maximizing the UE throughput rather than the connection rate. Let ρ_m denote the ratio of the number of active CRUs deployed in the hotspot when the average UE throughput is maximized, Fig. 10 shows the tendency of ρ_m for the number of active CRUs N_{C_act} at $N_U = 10000$. When N_{C_act} is small, deploying active CRUs widely in the area ($\rho \simeq 0.0$) can improve UE throughput because active CRUs connect to more UEs outside the hotspot. On the other hand, when N_{C_act} is large since more than a certain number of active CRUs can be deployed in the entire area, active CRUs can satisfy the communications demand of UEs in the hotspot. Since half of the UEs in this simulation are located in hotspots, ρ_m asymptotically approaches 0.5 at $N_{C\_act} \geq 5000$.

C. SIMULATION RESULTS: DIFFERENCE IN CHARACTERISTICS BETWEEN DAYTIME AND NIGHTTIME

Here we observe the system performance with the nighttime when the number of UEs in the area is smaller, i.e., $N_U = 2000$. Half of the UEs are assumed to be present in the hotspot, the same as in the daytime. Fig. 11 shows the characteristics of the ratio of activated CRUs, ρ_m, that achieves the maximum UE throughput with the number of active CRUs. For comparison, results for $N_U = 10000$ as the daytime are also plotted. The horizontal axis is N_{C_act} normalized by N_U. When N_{C_act} is small, unlike the daytime, deploying all active CRUs in hotspots ($\rho \simeq 1.0$) is expected to improve UE throughput for $N_U = 2000$. This is because UE density outside the hotspot is sparse, and activating CRUs for UEs outside the hotspot would be inefficient. When N_{C_act} is large, the value approaches 0.5, which is the same as the case of $N_U = 10000$. Since the density of UEs outside the hotspot is low for $N_U = 2000$ case, the UE throughput can be improved by keeping the active CRU ratio at the hotspot around $\rho = 0.6$.

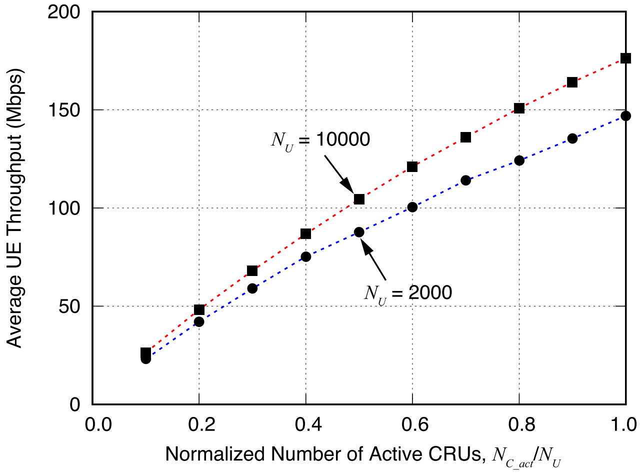

FIGURE 12. Average UE throughput with the normalized number of active CRUs.

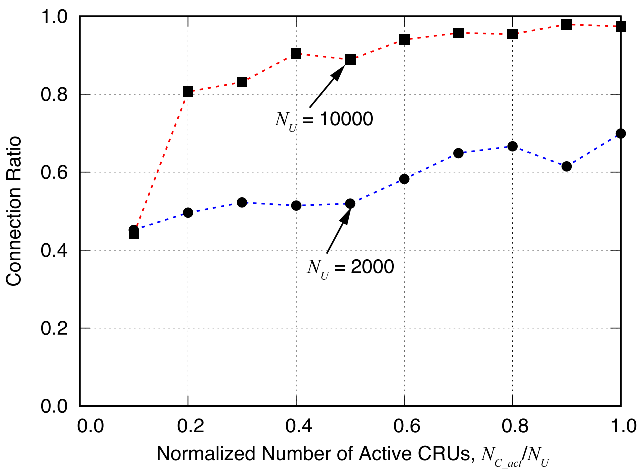

FIGURE 13. Connection ratio with the normalized number of active CRUs.

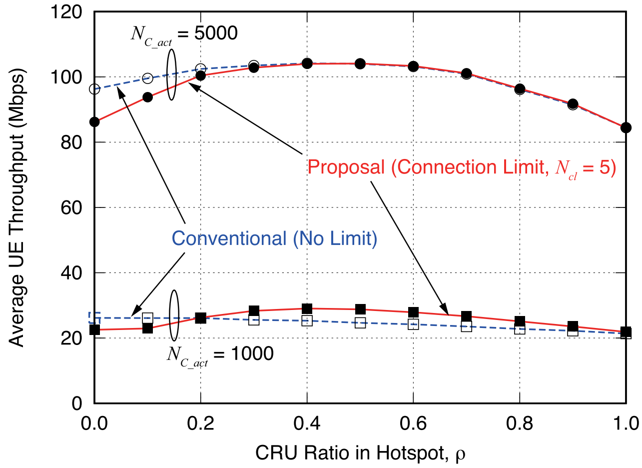

FIGURE 14. Average UE throughput as a function of CRU ratio in the hotspot.

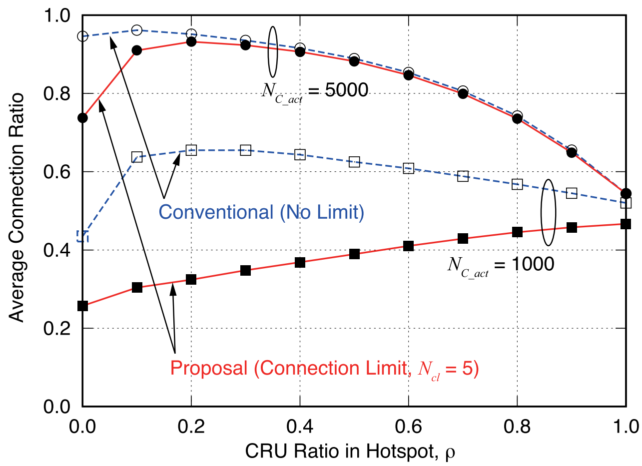

FIGURE 15. Average connection ratio as a function of CRU ratio in the hotspot.

Fig. 12 shows the average UE throughput characteristics as a function of the number of active CRUs normalized by N_U. The values of ρ_m in each horizontal axis are those obtained in Fig. 11. The average UE throughput increases as N_{C_act}/N_U increases, and the $N_U = 10000$ (daytime) case achieves 20% higher throughput than $N_U = 2000$ (nighttime) case. This is because $N_U = 10000$ has a large number of CRUs in the area, which can connect to many UEs and satisfy the communications demand. The connection ratio of UEs to the number of active CRUs is shown in Fig. 13. It increases as N_{C_act}/N_U, and $N_U = 10000$ case with a large number of the active CRUs in the area has a connection ratio about 1.5 times higher than that of $N_U = 2000$ case. On the other hand, both N_U case shows the same connection ratio at $N_{C\_act}/N_U = 0.1$. For $N_U = 2000$, the value of ρ_m is 1.0, which indicates the active CRUs are connected only to UEs in the hotspot. Meanwhile, when $N_U = 10000$, ρ_m is 0.0, active CRUs are connected to UEs distributed in the whole area. This results in showing almost the same connection ratio of around 0.5, where half of UEs inside/outside hotspots are connected to the active CRUs for daytime/nighttime. This result confirms that our proposed concept works to maximize user demand satisfaction by having spatiotemporal dynamics.

D. SIMULATION RESULTS: THROUGHPUT CHARACTERISTICS WITH UPPER LIMIT ON NUMBER OF CONNECTIONS

UEs have the ability to select the CRU to which they are connected. This sometimes result in a high concentration of connections to a particular CRU. Since the link between CRUs and UEs shares bandwidth B with the number of UEs connected, an increase in the number of connections resulted in a decrease in throughput. In addition, when CRUs are relocated, all UEs connected to them are immediately disconnected, causing a spike in control signals. To address this issue, the following simulation examines methods for reducing control signals by limiting the number of UEs that can connect to a CRU and distributing connections evenly among CRUs. Initially, each UE connects to the activated

CRU with the highest SINR. The CRU accepts the connection if the number of connections is less than N_{cl}, but rejects the connection if the number exceeds N_{cl}. If the connection is rejected, the UE tries to connect to the CRU with the second highest SINR. If all CRUs reject the connection, the UE resorts to connecting to a macrocell.

When the maximum number of connections is constrained to $N_{cl} = 5$, the average throughput performance of UEs is presented in Fig. 14, while the average connection ratio to CRUs is shown in Fig. 15. In this experiment, we set the number of UEs to $N_U = 10000$. For $N_{C\_act} = 1000$, the throughput is higher when the number of connections is limited to $0.2 < \rho < 1.0$. However, due to the small number of CRUs, the connection ratio to CRUs is reduced, as the number of potential reconnection destinations is also limited by the connection constraint. In this case, macrocells handle these overflowed connections. On the other hand, for $N_{C\_act} = 5000$, the throughput and the connection rate are similar for $\rho > 0.2$. This is because the number of candidate reconnection destinations is large, and a connection can be established to any of the CRUs. These results demonstrate that smoothing the number of connections is beneficial when the number of CRUs is large, while throughput improvement is expected by limiting the number of connections when the number of CRUs is small.

VI. CONCLUSION

This paper proposed a concept of adaptive C-RAN architecture for a smart city enabled by crowdsourced RUs to manage fluctuations in mobile traffic demand, which is caused by the spatiotemporal pattern of user mobility. The proposed network architecture contributes to the efficient deployment of mobile networks and better energy use. The edge server computes the optimum CRU states and activates/deactivates the CRUs based on the traffic information measured by RSUs. This paper presents the basic idea of the proposed architecture and its effectiveness is numerically analyzed in terms of areal demand satisfaction. User throughput performance are then elaborated through large scale system level simulations in an environment where half of the UEs are concentrated in hot spots. The results revealed the following trends:

1) In the daytime, as the number of UEs increases, active CRUs are uniformly distributed in the area when the number of CRUs is small, and when the number of active CRUs is large, about half of the CRUs are concentrated in hot spots.
2) In the nighttime, as the number of UEs is small, all active CRUs are concentrated in hot spots when the number of CRUs is small, and about half of the active CRUs are concentrated when the number of CRUs is large, which can improve the UE throughput performance.
3) To avoid a high concentration of connecting to a particular CRU, setting an upper limit for connecting to a CRU is also beneficial.

It constitutes future work to investigate further the details of the proposed architecture and a more comprehensive analysis of wireless transmission performance, e.g. constructing wireless backhaul to moving nodes as well as validating the system performance under the backhaul capacity constraint.

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