Cell Association for MTC Devices in 5G Networks: Schemes and Performance Evaluation

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***Abstract*—Fifth generation (5G) networks offer tremendous opportunities for Internet of things applications by facilitating massive machine-type communications (MTC). As many MTC devices are battery powered and intend to stay often in the sleep or power-saving mode, cell (re)association needs to be performed when a device wakes up. On the other hand, 5G networks are usually deployed as heterogeneous networks consisting of both macro and small cells under which a single device may be covered by multiple radio access technologies (RATs) simultaneously. Therefore, it is imperative to design effective cell association schemes for the purpose of efficient connectivity and resource utilization, especially when a device has multiple connectivity options. In this paper, three cell association schemes are proposed by considering a network scenario where multiple cells and different RATs are available for MTC devices. To perform cell association, received signal strength, channel occupancy status of neighboring cells, and directed handoff capability are considered as the criteria for our scheme design. Through analysis and extensive simulations, we demonstrate that superior system performance could be achieved for a given network by employing a suitable scheme that integrates multiple criteria and considers performance tradeoff.**

I. Introduction

The fifth generation (5G) wireless technology is the most recent rendering of cellular networks crafted to increase the efficacious delivery and responsiveness of wireless services and applications. The enhanced mobile broadband (eMBB) feature of 5G inherits intrinsic communication capabilities in mobile networks. Within eMBB, there are three distinct attributes 5G will deliver including higher capacity, enhanced connectivity, and support of higher user mobility. Additionally, 5G offers an innovative feature known as ultra-reliable low latency communications (URLLC). URLLC services are tailored to various vertical applications that require high reliability and low delay, for instance industrial automation, autonomous driving and Internet of vehicles. With URLLC, the efficiency and ultimate quality of the services delivered to end users will be asserted especially with respect to reliability and latency.

The third feature of 5G networks is its capability of supporting a vast range of massive Internet of things (mIoT) applications in forms of massive machine-type communications (mMTC). mMTC represents a novel communication paradigm not existing in earlier generations of mobile systems through which a huge number of devices are connected to the Internet directly/indirectly and have the ability to inter-communicate with each other without human intervention [1]. As an enabling technology for supporting another category of vertical applications that typically do not require high data rates, MTC is characteristic of small data and sporadic traffic.

High energy efficiency and long network lifetime are utmost important for the success of mIoT/mMTC applications. It is expected that the lifetime of MTC devices will last for 10 years or longer without battery replacement [2]. As MTC devices are typically battery-powered, it is a common practice that devices are programmed to sleep if no communication activity is required. The alternate of the active and inactive (sleep) behavior of devices can be realized with the help of techniques like discontinuous reception, power-saving mode, or wake-up radio (WuR) [3]. When a device stays in the power-saving mode or is operated based on WuR, it is disconnected from the network and hence not immediately reachable.

On the other hand, MTC devices could be covered by more than one cell and multiple radios access technologies (RATs) since a 5G network may consist of multiple heterogeneous cells with overlapping regions. Consequently, under the above mentioned power-saving or sleep mode, once an MTC device wakes up, it needs to be associated/re-associated to an appropriate cell and RAT [4]. It is therefore interesting to investigate how devices perform cell association based on given quality of service (QoS) requirements [5].

In the literature, many cell association algorithms exist targeting at various network scenarios as summarized in the next section. In this paper, we propose three cell association schemes for MTC devices by individually or jointly considering different network conditions including signal strength, traffic load, and directed handoff capability. The first scheme is contingent on the signal strength a device receives as the main criterion. The second scheme makes a decision based on both ongoing traffic load status and signal strength. Moreover, this scheme gives priority to ongoing traffic at the overlapping zone when assigning radio resources. The third scheme is proposed based on the concept of directed handoff [6]. This capability enables the process of transferring an ongoing data session from one channel to another so that the current channel could be released to other users.

The remainder of this paper is organized as follows. After

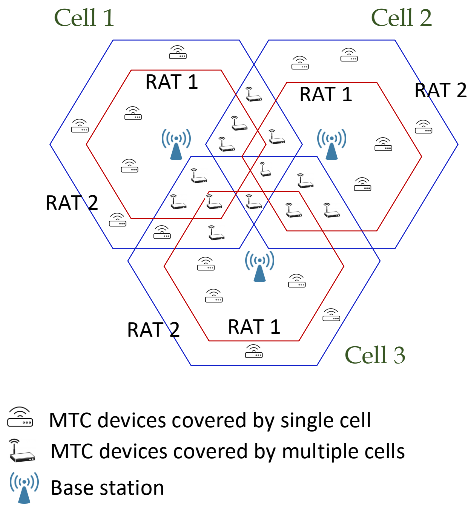

Fig. 1. Three cells with overlapping zones. Each cell has two RATs.

summarizing related work in Sec. II, the network scenario is outlined in Sec. III. Afterwards, we present the proposed cell association schemes in Sec. IV and system performance parameters in Sec. V, respectively. Moreover, Sec. VI presents numerical results and compares the performance of the cell association schemes. The conclusions are drawn in Sec. VII.

II. Related Work and Motivation

To perform cell association, many network scenarios have been envisaged and various criteria have been considered for decision making [7]-[12].

The authors in [7] studied small cell base station (BS) on/off strategies for improving energy efficiency in ultra-dense networks (UDNs). For user association in UDNs, signal-to-interference-plus-noise ratio (SINR), load balancing, and user mobility were considered as decision making parameters. Moreover, how to reduce frequent switching between users and small cell BS has also been considered in [7]. Moreover, [8] proposed a joint cell activation and selection scheme for energy efficiency in UDNs and created a three-layer iterative algorithm to solve the nonlinear mixed-integer programming problem. Therein, a QoS driven distributed cell association algorithm was proposed with the aim of maximizing the sum utility of rate or minimizing the global outage probability. This is achieved by allowing users to receive many resource blocks that are adequate to fulfill their QoS constraints. The work performed in [9] focused on a class of novel user association schemes. First, joint cell association and resource allocation were considered. Then a distributed algorithm via dual decomposition was formulated and it was proven to converge to a near-optimal solution with low complexity.

Furthermore, [10] examined pricing-based BS association schemes for heterogeneous networks and suggested a distributed price update strategy based on a coordinate descent algorithm. Another user association algorithm was proposed in [11] considering switching-on/off for BSs in heterogeneous networks composed of cellular networks and wireless local area networks. Owing to the on/off behavior of BSs, that algorithm can reduce energy consumption significantly compared with the case where BSs are always kept on.

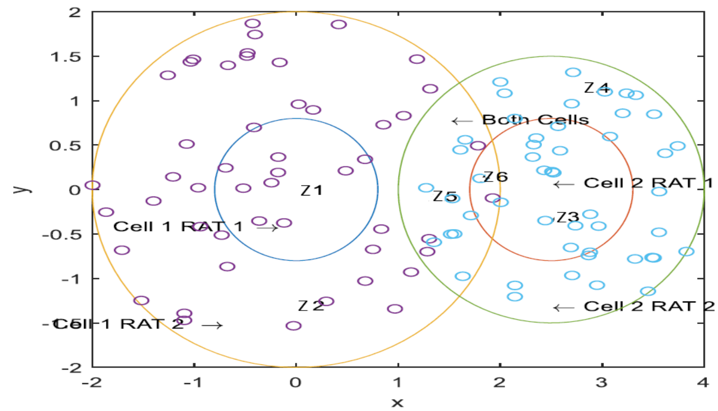

Fig. 2. Two cells with overlapping zones. Each cell has two RATs.

According to the existing studies summarized above, signal strength-based cell association does not always provide best performance for the attached devices, especially in a dense network. For a network in which a large number of MTC devices are operated under the power-saving or sleep mode, it would be beneficial to perform cell association by considering both signal strength and traffic conditions of each cell. On the other hand, when one or multiple cells are operated based on multiple RATs covering different geographical zones, it is necessary to check the availability of RATs in the residing and neighboring cells for achieving better connectivity. These observations on existing research triggered our motivation to study cell association for MTC devices, as presented below.

III. Network Scenario and Assumptions

In this study, we consider a multi-cell heterogeneous cellular network where a number of MTC devices are deployed and some of these devices may be covered by more than one RAT, as depicted in Fig. 1. Moreover, all devices are deployed as static. However, they exhibit random on/off behavior due to the alternate power-saving and active mode. For the simplicity of analysis, circular cells are considered in our scenario for scheme design and performance analysis as such cells provide overlapping zones with each other. As shown in Fig. 2, the total area of interest is divided into 6 zones, denoted as $Z_i,\ i = 1, 2, \cdots, 6$ respectively. Note that these six zones are non-overlapping, i.e., $Z_i \cap Z_j = \emptyset,\ \forall i, j, i \neq j$.

MTC devices require cell association to a BS under various incidences, e.g., at the initial deployment stage, when they wake up from the power-saving mode, or when a wake-up call is received by WuR enabled devices. Consider battery-powered MTC devices with sensing and communication capabilities. While staying often or mostly in the sleep or power-saving mode for the purpose of energy conservation, the aforementioned cell association procedure is required when devices become active again, either periodically or aperiodically. For event-driven sensing and communication, MTC devices need to wake up once an event is triggered, requiring also cell association before data reporting. In this study, all devices are assumed to follow an on/off behavior under one of the above mentioned incidences. Accordingly, a device becomes active (on) after a sleep (off) period, and vice versa. The active and the sleep (idle) periods are assumed to be exponentially distributed with mean times $1/\mu$ and $1/\lambda$ respectively, where $\mu >> \lambda$ since generally the average sleep time of an MTC device is much longer than the duration of an active period.

In our scenario, each cell is operated based on two RATs. While RAT 2 of each cell guarantees the coverage across the entire cell coverage, RAT 1 only covers a circular area limited by a certain distance from the cell center with shorter coverage. For instance, while RAT 2 might support global system for mobile communications (GSM) or wideband code-division multiple access (WCDMA) services, RAT 1 provides only long-term evolution (LTE) or new radio (NR) services. MTC devices are distributed across the area of interest randomly, following a binomial point process. As shown in Fig. 2, some MTC devices are covered by both cells and multiple RATs. For instance, the devices located within Zone Z_6 are covered by three RATs, i.e., RAT 2 of both cells and RAT 1 of Cell 2. Such a device, therefore, has multiple options (in this example, 3 options) to select a connection with a BS once it transfers to the active status from the sleep or power-saving mode.

IV. Proposed Cell Association Schemes

To perform cell association, we propose three schemes in this section. From here onwards, we use notations C1R1 and C1R2 to represent RAT 1 and RAT 2 operated in the corresponding zones of Cell 1 respectively. Similar notations apply to Cell 2. Generally, each BS simultaneously serves multiple users. Thus, devices covered by the same BS need to share resources such as time slots and frequency channels. For our scheme design, we consider a set of predefined channels which is allocated for each RAT. Moreover, the channel occupancy of a RAT at a particular time instant is directly proportional to the total number of devices associated with it.

A. Scheme I: Signal strength-based Cell Association

Let us start with a simple scheme which considers only signal strength. With this scheme, the received signal strength at each device is selected as the decision making criterion for cell association.

Before performing cell association, the signal received at an MTC device which is located at distance d away from the transmitter of a BS needs to be obtained. Denote by P_r and P_t the receive and transmit power respectively. Then the ratio of the received to the transmitted power is obtained by

$$\frac{P_r}{P_t} = \frac{G_{rt}\chi^2}{(4\pi^2)d^\alpha L} \tag{1}$$

where G_{rt} is the product of the transmitter and receiver antenna gains, L is the system loss, χ is the signal wavelength, and α is the path loss exponent [13]. For free space, $\alpha = 2$.

For all schemes, we consider that MTC devices have a priori knowledge on their locations in terms of geographical coordinates in the area of interest, obtained from initial deployment, via BS signaling, or inbuilt positioning facility. Accordingly, each device can calculate its distances to the BSs that are located nearby. Based on the single strength obtained from (2), cell association can be performed. If a device is located at a point covered by several BSs, then it selects the BS from which it receives the strongest signal. Moreover, if it is covered by both RATs in that cell, the device is attached to RAT 1 if a channel is available. Otherwise, it selects RAT 2. In case that no available channel exists in that cell, the device selects the next closest BS.

Refer to Fig. 3 for a simple example. When device D6 located in Zone ⑥ wakes up from the sleep mode, the order of the cell selection for this device will be C2R1, C2R2, and C1R2, respectively, since the Cell 2 BS is the closest one to D6. In this example, C1R1 is not possible since D6 is not in the coverage zone of C1R1. Therefore, if all channels in C2R1, C2R2, and C1R2 are occupied, the request will be blocked.

B. Scheme II: Traffic Load based Cell Association

Although the number of channels in each RAT plays a role in Scheme I, the carried traffic load in each cell is not included for cell association decision making. In Scheme 2, a joint criterion integrating both traffic load and received signal strength is introduced in order to accommodate MTC devices to the most suitable RAT among available cells and RATs.

In Scheme II, we intend to balance traffic load among BSs. Correspondingly, the traffic load distribution among neighboring cells is taken into account as the main decision making criterion in addition to the received signal strength when performing cell association. More specifically, if an MTC device is covered by multiple cells, the scheme first checks the closest BS's channel occupancy. Channel occupancy of the i^{th} cell, η_i, is determined by the ratio between the number of occupied channels and the total number of channels including all RATs in that cell. We configure a threshold level for the traffic load of i^{th} cell as γ_i where $0 < \gamma_i < 1$. If the cell with the strongest P_r (say i^{th} cell's) channel occupancy is less than or equal to the pre-configured threshold level, i.e., $\eta_i \leq \gamma_i$, that cell will be selected. However, if the channel occupancy exceeds the threshold, i.e., $\eta_i > \gamma_i$, then the device tries the BS with the second highest P_r. This procedure proceeds until the device finds a BS which has its channel occupancy below the threshold level. When such a cell is found, its RAT 1 will be the preferable choice if it covers the device and a channel is available. Otherwise, RAT 2 of the same cell is selected. By adjusting γ_i, load balancing among cells can be achieved.

If $\eta_i > \gamma_i$, $\forall i$, then cell selection is performed according to the strongest signal strength as presented in Scheme I. In other words, Scheme I can be regarded as an especial case of Scheme II when $\gamma_i = 1$ for all i.

C. Scheme III: Handoff enabled Cell Association

As an enhancement of Scheme II, we consider the applicability of handoff among available channels and propose Scheme III. The enhancement is to enable directed handoff [6] for MTC devices operated with RAT 2 to switch to a channel in RAT 1 if applicable. This handoff is required when a

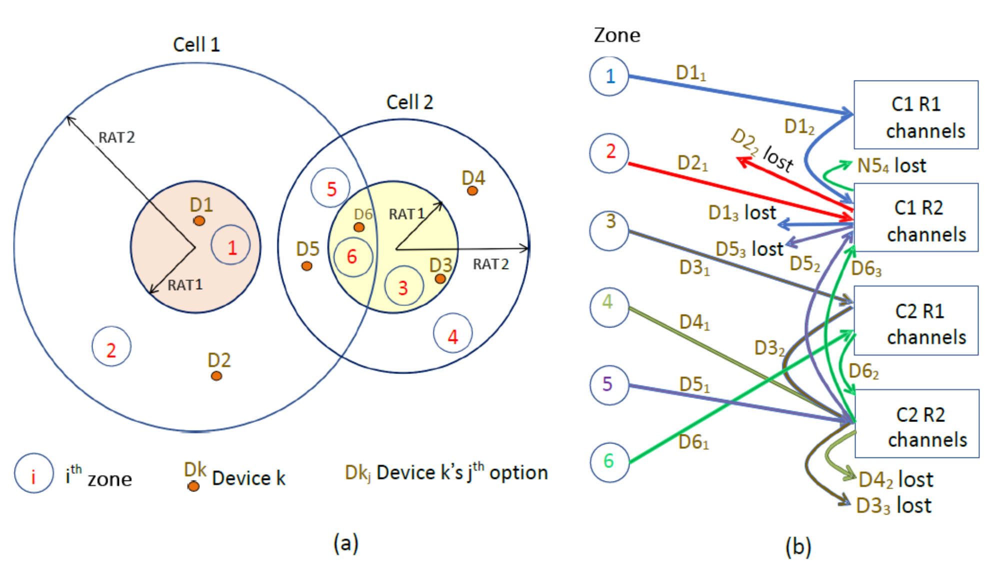

Fig. 3. Illustration of cell association with directed handoff for nodes at different zones.

device wakes up from a zone where only a RAT 2 coverage is available and all channels are occupied or the traffic load has reached the threshold.

Thanks to the access opportunities offered by directed handoff, an MTC device that would be blocked due to channel unavailability in Scheme II could survive when Scheme III is employed. This advantage is provided by another device that is located in a zone of the same cell with the coverage of both RATs. More specially, the device that is occupying a channel in RAT 2 performs directed handoff to a vacant channel in RAT 1. Thus, its occupied channel is released to the new request. Anyhow, if all channels in RAT 1 are also busy, then the new request would still be blocked.

Refer to Fig. 3 for another example. Device D2 is covered by C1R2 only. When it requires cell association, its request would be rejected if all channels in C1R2 are occupied (for Scheme I) or Cell 2 is overloaded (for Scheme II). When Scheme III is employed, however, its request could be accepted once another device, e.g., D5, releases its channel by directed handoff to C2R2 as D5 is covered by both C1R2 and C2R2.

V. Performance Evaluation

To assess and compare the performance of the proposed schemes, we define three metrics, i.e., cell association probability, fairness index, and handoff ratio, as presented below.

A. Cell Association Probability

Cell association probability (CAP) is determined by the number of blocked requests versus the total number of requests during the observation time. Due to the instantaneous channel unavailability in different RATs, some new requests may be blocked in all three schemes. However, the way how a new request is blocked differs from each other in the proposed schemes according to the principles presented above. For instance, the blocking probability in Scheme I and Scheme II would be higher than in Scheme 3 since directed handoff which could reduce the number of blocked requests is not applicable in the former two schemes.

Denote by N_b and N_t the number of blocked requests and the total number of requests, respectively. The CAP can be obtained as follows.

$$CAP = 1 - \frac{N_b}{N_t}. \tag{2}$$

B. Handoff Ratio

The handoff ratio, denoted by H_r, is equal to the number of handoffs performed during the observation time, N_h, divided by the total number of admitted requests. That is,

$$H_r = \frac{N_h}{N_t - N_b}. \tag{3}$$

C. Fairness Index

Fairness measures provide a means in network engineering to assess fair resource allocation among different users (i.e., cells in this study). To evaluate the fairness of resource allocation achieved in the proposed schemes, a popular mathematical definition known as Jain's fairness index is adopted.

Given a set of n data $y = \{y_1, y_2, \cdots, y_n\}$, where $y_i \in \mathbb{R}$ and $y_i \geq 0$, Jain's fairness index is defined as

$$J(y) = \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n \sum_{i=1}^{n} y_i^2}. \tag{4}$$

Note that, in the proposed schemes, the y_i term is the number of resource units (channels) allocated at the i^{th} cell. According to this index, the value of $J(y)$ is bounded between 0 and 1. Moreover, its value is 1 only if all y_i values are equal, i.e., it is maximum when all cells receive the same allocation [14]. The higher the $J(y)$ for a scheme, the fairer the scheme.

VI. Numerical Results and Discussions

In this section, the performance of the proposed cell association schemes is investigated through extensive simulations. A custom-built simulator is developed in MATLAB with the three schemes implemented.

TABLE I
SIZE AND NUMBER OF DEVICES IN THE SIX ZONES SHOWN IN FIG.3

	Zone ①	Zone ②	Zone ③	Zone ④	Zone ⑤	Zone ⑥
Calculated area (squared units)	2.011	8.895	2.619	2.789	1.138	0.522
Average number of devices, N_{avg}	10.8	32.0	17.7	18.9	14.0	5.7

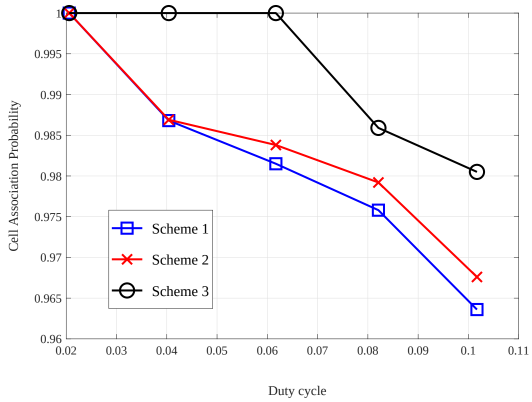

Fig. 4. Comparison of cell association probability as duty cycle varies.

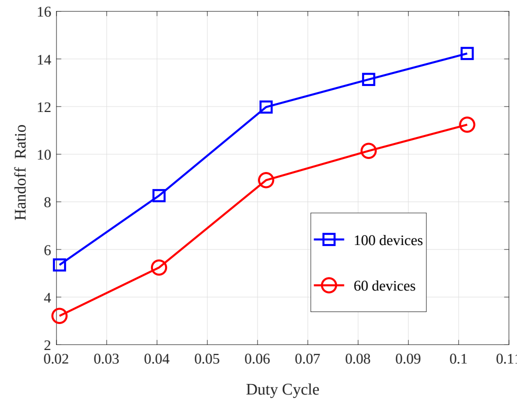

Fig. 5. Handoff ratio for Scheme III as duty cycle varies.

A. Simulation Configuration

Without loss of generality, we deploy an MTC network as shown in Fig. 3 with 100∼500 devices distributed across two cells and configure $\alpha = 2$. The behavior of the MTC devices follows exponential on and off times. The radius of the circular areas covered by RAT 1 is set as 0.8 km for both cells. For RAT 2, it is configured as 2 km and 1.5 km of Cell 1 and Cell 2, respectively. Moreover, the total numbers of channels that can be allocated at a time in RAT 1 and RAT 2 are set as 8 and 10 respectively for each cell. The sizes of the six zones illustrated in Fig. 3 are listed in Tab. I. Accordingly, the average numbers of devices residing in those six zones are estimated as shown in the table by performing multiple runs of simulations and taking their average values. For Scheme II, we configure $\gamma_1 = 0.5$ and $\gamma_2 = 0.6$.

Furthermore, the mean values of the on and off times are the inverse of $\mu = 3.80$ and $\lambda = 0.08 \sim 0.44$ time units respectively. Based on these values, the duty cycle of a device which is an input parameter for our performance evaluation is obtained as follows.

$$\text{Duty cycle} = \frac{\text{Mean On Time}}{\text{Mean Total time}} = \frac{1/\mu}{1/\mu + 1/\lambda} = \frac{\lambda}{\lambda + \mu}. \quad (5)$$

Duty cycle in this study is defined as the ratio of the operating time of an MTC device under communication to the total time during a given observation period. In other words, duty cycle is the fraction of a period in which a device is active. Thus, a 5% duty cycle means that the device is active for 5% and off for 95% of the observation time.

B. Impact of Duty Cycles on CAP

The performance of the cell association probability for the three schemes as duty cycle varies is shown in Fig. 4. To alter the duty cycle, the duration of the off phase of the cycle is varied while keeping the on duration as constant. As can be observed from this figure, the CAP decreases with a larger duty cycle value for all three schemes. This is because the number of devices in the active mode increases when the duty cycle becomes larger, i.e., with a shorter off time period. Consequently, more requests from MTC devices will be blocked when all communication resources are occupied.

However, performance distinctions exist among the three schemes. Compared with Scheme I, Scheme II achieves better performance in terms of the CAP. This is evident only at higher duty cycle values. The reason can be explained as follows. When the active period is (very) low, the channel occupancy of both cells is (far) below saturation or the threshold level γ_i. Under such circumstances, Scheme I and Scheme II do not make any different decisions regarding possible blocking of any new requests. However, once the active period is large, i.e., under high duty cycles values, channel allocation of those two schemes becomes diverse. More specifically, Scheme I does not consider load balancing among cells. Nor does it consider handoff. Therefore, its CAP performance is (much) lower than that of Scheme II which considers load balancing.

On the other hand, Scheme III exhibits the best performance in terms of the CAP among all three schemes. This is because it applies directed handoff when necessary by transferring active sessions from one RAT to another less loaded one upon new arrivals. Owing to this feature, the requests which tend to be blocked in the other two schemes can be accommodated to the network, at the expense of handoff overhead. In the next subsection, we explore this cost in detail.

C. Handoff Ratio

Fig. 5 illustrates the obtained handoff ratio for Scheme III as defined in (3). As shown in the figure, with an increasing duty cycle, the handoff ratio also rises. At low duty cycles where the active number of devices is less, handoff requirements occur seldom. When duty cycle becomes comparatively large, more devices become active and new requests in RAT 2 would be blocked if no channels are available or the traffic load threshold has been reached, if Scheme I or Scheme II is

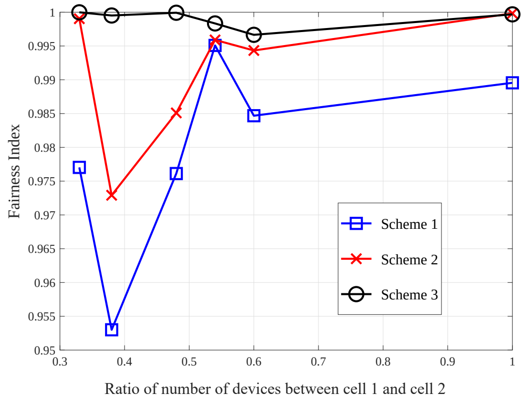

Fig. 6. Fairness index as the ratio of device numbers between two cells varies.

employed respectively. In Scheme III, if there are devices located within the coverage zone of RAT 1 but occupy RAT 2 channels, the system attempts to perform handoffs from RAT 2 to RAT 1 to avoid blocking new requests given that a RAT 1 channel in the same zone is also available for transmission. The higher the duty cycle, the more frequent the occurrence of handoffs. The benefit brought by this protocol cost is the increased CAP for Scheme 3, as observed in Fig. 4.

On the other hand, when comparing the handoff ratio performance with different device populations, it is evident that a small number of devices leads to a lower number of handoffs. This is because the network resource is configured the same for both device populations. With less offered traffic from a smaller number of devices, fewer handoffs are needed.

D. Fairness Index

Fig. 6 depicts the achieved fairness by the three cell association schemes as the ratio of the number of devices located in Cell 1 and Cell 2, denoted by β, varies. When $\beta = 1$, there are the same number of devices in each cell. With $\beta = 0.5$, there are twice many devices in Cell 1.

For Schemes I and II, when the node distribution between the two cells is uneven, the fairness index becomes lower since in both schemes the distance to the BS is a crucial parameter for signal strength. For instance, if 80% of the devices are located within a particular cell, the association scheme based on signal strength does not have any other choice than selecting the nearest cell. Therefore, when traffic load η is low, Scheme I mostly selects the nearest cell for association leading to least fairness. Scheme II achieves better fairness thanks to its consideration of load balancing.

Across the whole range of device distribution ratios, the highest fairness index is achieved by employing Scheme III. In Scheme III, device requests can be fairly accommodated among cells since directed handoff is enabled in addition to signal strength and load distribution. Indeed, the achieved fairness index is close to one meaning that radio resources are equally and fairly allocated among neighboring cells, even if device distribution is unbalanced in different zones.

VII. Conclusions

In this paper, three cell association schemes are proposed and evaluated considering a scenario in MTC networks where devices are operated under low duty cycles aiming at power saving. While Scheme I makes cell association decisions merely based on the received signal strength from nearby base stations, Scheme II checks the load distribution among neighboring cells as an additional criterion. Consequently, better performance is achieved in Scheme II in terms of both cell association probability and fairness index. As a further enhancement beyond those schemes, Scheme III enables directed handoff between two RATs within a cell or across two cells. It outperforms the other two schemes in terms of cell association probability as well as fairness. However, such a privilege for Scheme III is achieved by performing handoff operations which incurs additional protocol overhead to the network. The findings of this paper provide a deeper insight into scheme design and performance improvement for cell selection and association in energy constraint MTC/IoT networks.

VIII. Acknowledgment

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