Final version appears in IEEE Trans. on Wireless Communications, 2016.

Incentivizing Selected Devices to Perform Cooperative Content Delivery: A Carrier Aggregation based Approach

Bidushi Barua, Zaheer Khan, Zhu Han, Alhussein A. Abouzeid, and Matti Latva-aho

***Abstract*—In a cooperative content distribution (CCD) using multiple interfaces, a smart wireless device receives content from a base station (BS) on its cellular interface, and it broadcasts the same content through another wireless interface, such as WiFi. However, different users can experience different link qualities, and users with slow wireless links can be a bottleneck in terms of CCD performance. To address this problem, we propose a device selection method which leverages multiple interfaces of the selected devices to perform CCD. Our proposed method takes into account the link quality of both primary (cellular) and secondary (WiFi/short-range) interfaces of the devices, and selects the devices with the best link quality for CCD. To analyze the stability of the proposed CCD method against selfish deviators, we model the problem as a repeated CCD game. We show that although the proposed method yields significant gains in terms of energy and frequency carrier savings, it is vulnerable to selfish deviating users. To address this challenge, we propose a *carrier aggregation* based incentive mechanism. The analytical and simulation results show that the proposed mechanism maximizes individual and network payoffs, and is an equilibrium against unilateral selfish deviations.**

***Index Terms*—Cooperative content delivery, multiple wireless interfaces, efficient off-loading, incentive mechanism, carrier aggregation and game theory.**

I. INTRODUCTION

Over the last few years the surge in new smart device users has led to a phenomenal growth in mobile/cellular data traffic. As the developing world is expected to add more than 400 million new users of smart devices to the global network, the growth in demand for data traffic is expected to continue [2], [3]. To address this challenge the wireless industry is preparing for a long term 1000 times more data traffic in cellular networks [3]. Though smart devices are content hungry, over the years, these devices have exhibited advanced features, such as support for large memory space, increasing processing capabilities, and also support for using multiple interfaces (such as cellular and WiFi).

In the current cellular networks, the default method of distributing content among users is by independent downloading of the requested content by each user using their own cellular links [4]. This currently used default method of operation can lead to cellular traffic congestion in scenarios where many users (that are in proximity of one another) demand rich content applications. The availability of multiple wireless interfaces on smart devices could potentially enable these devices to operate in heterogeneous environments and use diverse protocols, such as cellular and WLAN protocols. These features have attracted the interest of researchers to use multiple wireless interfaces in the context of cooperative content delivery (CCD). For instance, the works in [5], [6] have shown that the problem of congestion can be mitigated if the available multiple interfaces on smart devices are utilized intelligently to disseminate data contents among a group of users that are in the vicinity of one another.

Several practical use cases of CCD have been discussed in different works, a few of which include (but are not limited to): 1) Devices that simultaneously request the same data content. For instance, when a group of devices want to watch a video (such as a live game or a popular YouTube content) simultaneously. It is in general not comfortable for more than one user to watch the video together on one phone/tablet screen; 2) Devices that asynchronously request for the same popular content. For instance, a group of people who are interested in watching on their devices the same popular audio/video content but at different times; and 3) Software updates on smart mobile devices at regular intervals of time. The practical use cases of CCD using multiple interfaces for a group of smart phones at close proximity, can also be found in areas beyond the field of entertainment. Documentary videos and educational movies can enhance the learning process adopted by educators in a classroom [7].

In this paper, we study the problem of selection of best devices for CCD using multiple interfaces under scenarios in which two or more devices are in the vicinity of one another and request the same content simultaneously. The main contributions of this paper are:

- We propose a method called Select Best (SB) to perform selection of devices for CCD. Our proposed device selection method takes into account the quality of both primary (cellular) and secondary (WiFi) links of users that are interested in the same content. The proposed method incurs little overhead as it utilizes information (such as acknowledgments of content packets) for device selection, which already exists in the network.
- We compare the proposed method against three different methods and show that the proposed method is efficient in terms of frequency carriers and energy savings performance. Moreover, in our performance evaluation, we take into account the impact of the presence of independent competing links (such as competing users in the unlicensed band), and also the impact of mobility on the performance of the proposed method.
- In our model, although the cellular BS assists in CCD,

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This work was funded by the Academy of Finland (Grant numbers 268997 and 268830), and in part by the U.S. National Science Foundation (NSF) under Grant ECCS-1547201, Grant CCF-1456921, Grant CNS-1443917, Grant ECCS-1405121, and Grant NSFC61428101. Preliminary results of this paper were presented in [1].

each device is considered as an independent entity which acts to maximize its own payoff and can deviate from the proposed CCD method if a deviation increases its utility. We consider the impact of selfish strategies on the performance of the proposed method, i.e., the strategies in which a device deviates from the BS selection to maximize its payoff. One example of such strategies is the strategy where a selfish device is willing to receive contents from other devices via WiFi interface; however, to maximize individual payoff, it does not transmit content to other devices.

- We utilize the framework of repeated games with an infinite time horizon to model the interactions of users participating in CCD. We show that CCD using multiple interfaces of the best selected devices is vulnerable to selfish deviating users which poses a “tragedy of the commons” dilemma [8]. To address this challenge, we propose a *carrier aggregation* (CA) based incentive mechanism called the Follow-Reward and Disregard-Punish (FRDP) mechanism. The proposed mechanism rewards the devices that follow the BS selection by giving them higher cellular rates. Higher cellular rates are achieved using aggregation of those carriers that are saved due to CCD using the SB method. When a user is selected to broadcast the same received content and the user disregards the BS’s selection, the user is punished in the next rounds by giving content to it only through a single cellular carrier.
- Finally, using the analytical and simulation results we show that the SB method with FRDP mechanism maximizes individual and network payoffs, and is also an efficient equilibrium against unilateral selfish deviations.

The rest of the paper is structured as follows: In Section II, we review the related work. Section III presents the system setup and Section IV presents the proposed SB method. In Section V, a game theoretic formulation and stability analysis of the proposed CCD method are presented. Section VI presents and evaluates a CA based incentive mechanism for the SB method. The simulation results are then described in Section VII. Finally, Section VIII draws conclusions.

II. RELATED WORK

In a hybrid wireless network both infrastructure-based and infrastructure-less (i.e., ad hoc mode or peer-to-peer mode) communications can be used by wireless devices. Cooperative communications in hybrid wireless networks, where some devices are used to relay the source signal to other devices is an intensively studied topic. The works in [9], [10] consider the use of cooperative packet delivery for coverage extension scenarios where a mobile node which is out of the transmission range of a BS is forwarded data by other nodes carrying data from the BS or they utilize cooperation to serve users in *dead spots* in a cell, i.e., the spots which are not reachable by a BS in a single hop. The works in [11] study hybrid networks using a single cellular interface. These works consider device-to-device (D2D) LAN underlaying a cellular uplink, where multiple D2D users (DUs) intend to communicate with a D2D receiver. The works in [12], [13] consider the use of cooperative packet delivery in hybrid networks between devices that want to communicate data with each other, are in the same area and they communicate using ad hoc mode as routing them through the BS can be very wasteful. Although all these works study cooperative packet delivery in hybrid wireless networks they are fundamentally different from our work in the following ways. Our work considers the scenarios where multiple devices are simultaneously interested in the same content, and proposes a method to reduce the number of cellular carriers utilized in content delivery to multiple users simultaneously. We focus on the problem of selection of best devices that can perform CCD using their WiFi interfaces. Moreover, since use of their WiFi interfaces for CCD require energy expenditures by mobile devices we also model the CCD scenarios as a game in which the impact of selfish interactions between users are taken into account.

Broadly speaking, the works that exploit multiple wireless interfaces for CCD to users that demand the same content can be divided into two categories: 1) Methods in which two or more devices that are in close proximity, request the same content at different times [5], [14]. The works in [5], [14] study such methods, where a device downloads the content using a primary interface and stores the content locally. A device then opportunistically exploits its secondary interface to either cooperatively deliver or download content to/from those devices that come in close contact and are interested in the same content. 2) Methods in which two or more devices that are in close proximity, simultaneously request the same content. Generally, in these methods the devices employ a primary interface (such as the cellular interface) for downloading the data content, and simultaneously use a secondary interface (such as WiFi or Bluetooth (BT)) for cooperatively sharing/distributing the content to other users nearby. Our work and also the works in [4], [15], [16] study the simultaneous content request/delivery scenarios. However, our work focuses on saving cellular carriers by using cellular interfaces of selected users for cooperative content delivery using their WiFi interfaces, while the methods proposed in [4], [15], [16] focus on techniques that use multiple interfaces of all users in a group. For example, in [15], each device downloads part of video content (a content segment) from the server. The received content segment is then exchanged among the users by cooperatively broadcasting it by each user to other users in the group. Unlike our work, each user in these works is assumed to be trustworthy and always cooperative. Moreover, different from all the above mentioned works, we also provide a carrier aggregation based incentive mechanism to discourage selfish deviations in mobile content delivery scenarios. We also study the stability of the proposed incentive mechanism using the framework of repeated games. Finally, different from all the above mentioned works, we also consider the impact of mobility on the performance of the proposed method of cooperative content delivery.

The works in [17], [18] and [19] consider single user scenarios and study performance in terms of energy and throughput of a cellular and a WiFi interface to deliver content. Unlike these works, we study multiple user scenarios and propose a method to select users with the best links (best cellular/WiFi interfaces) to broadcast contents to other users in their vicinity. The work in [20] considers multi-user scenario for CCD using cellular and a short range interface. However, the work has many differences such as: 1) The short range interface considered is not WiFi but a unicast/multicast interface; 2) the distributed method proposed in [20] do not consider performance of both cellular and short range to select the users for CCD; and 3) the nodes exchange energy consumption information of their short range interface with one another. These differences make the problem studied in [20] different from our problem.

The design of mechanisms aimed at incentivizing/punishing users in wireless networks to achieve cooperation is an extensively researched topic [21]–[24]. A reputation-based framework for efficient spectrum access in cognitive radio networks was proposed in [21]. The authors in [22] proposed an incentive scheme based on reduced charging for users that deliver content to other users in peer-to-peer networks. The work in [23] used a Stackelberg game model to incentivize distributed nodes to forward content to other users in video-on-demand service systems. The authors of [24] proposed and examined different incentive schemes based on pricing to overcome the free-riding problem in content sharing over peer-to-peer networks. Different from all these works, we focus on the scenarios where users demand the same content, and we need to design incentive/punishment mechanism for selected best devices that perform CCD using multiple interfaces. Moreover, unlike other works which propose abstract or virtual-currency based reward models, we propose a new carrier aggregation based incentive/punishment mechanism which can be easily implemented at a base station without major modifications.

As discussed above, using theoretical and numerical analysis several different works have shown that CCD using multiple interfaces can improve the content delivery performance of cellular networks. However, to evaluate the content delivery performance using multiple interfaces, real-time measurements using different interfaces for content delivery are equally important. Several different works in [25], [26] (see also references within) have performed real measurements to evaluate the energy and throughput performance of different wireless interfaces for content delivery. In summary, the measurement based works in [25], [26] point to the following conclusion: In terms of content delivery, WiFi performs better in terms of average energy efficiency and average content delivery rate as compared to cellular and BT technologies.

In [1], we considered the problem of selection of best devices for cooperative content delivery (CCD) using multiple interfaces. In this paper, we extend our previous work in [1] to the case where each device is an independent entity who acts to maximize its own utility. This extension dramatically changes the structure of the problem studied in [1] because a device can now deviate from a CCD method if a deviation could increase its utility. To address this challenge, we utilize the framework of repeated games with an infinite time horizon to model the interactions of users participating in CCD. Using analytical and simulation results we also show that the method proposed in [1] can be vulnerable to free-riding users. To address this challenge, we propose a carrier aggregation based incentive mechanism called the Follow-Reward and Disregard-Punish (FRDP) mechanism for the proposed SB method. Using analytical and simulation results we show that the proposed incentive mechanism maximizes individual and network payoffs, and is also an efficient equilibrium of the game. Moreover, different from [1] we also consider the impact of mobility on the proposed SB method.

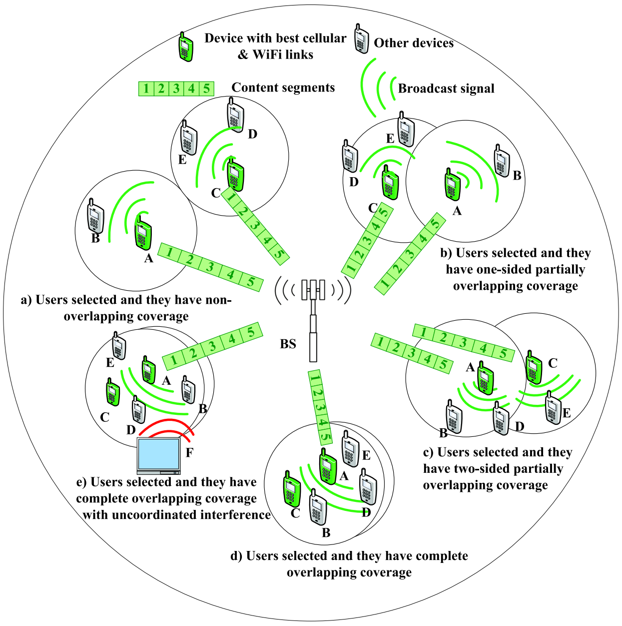


Fig. 1: System model of the studied problem with examples of different coverage overlapping scenarios for users that are interested in the same content.

III. SYSTEM MODEL

A. Network model

We consider a generic circular cellular cell of radius ρ_T in which the BS is located at the center of the circle. There are N users in the cell who are interested in the same content. In Fig.1 we illustrate the system model. Let $\mathcal{N} = \{1,2,3,\cdots,N\}$ represent the set of N users interested in the same content. The location of each user i, where $i \in \mathcal{N}$, is represented by the polar coordinates (d_i, θ_i), where d_i is the distance between the BS and user i, and $0 \leq \theta_i \leq 2\pi$ is the angle relative to the BS at the origin of the circular cellular cell. Two different distributions of N users are considered within the cellular cell: 1) Random distribution around the BS; and 2) Clustered distribution around the BS. For a given N, the number of users n_t in each of the n_c clusters can be different. However, to have N total number of users, we ensure that $n_c * n_t = N$.

B. Channel model

Under the scenarios where the traditional *default cellular mode* is utilized for content delivery, each user independently downloads content using its own cellular connection. When all N users utilize only the default mode then the BS needs to have N independent parallel sessions or carriers. When the cellular BS sends a content segment to a user i then we consider data rate as a measure of the quality of a communication link between the mobile station and the cellular BS. The instantaneous cellular rate at time t of the ith link $R_{C,i}(t)$ can be expressed as

$$R_{C,i}(t) = B_C \log_2 \left(1 + \frac{h_i(t) P_{B,i}}{B_C N_0}\right), \quad (1)$$

where $h_i(t)$ is the channel gain at the time t between the BS and user i, and is given as $h_i(t) = \frac{\kappa g_f(t)}{(d_i^{\alpha})}$ with κ being the path loss constant, α is the path loss exponent, d_i is the distance between the BS and user i, $g_f(t)$ is the fading gain at the time instant t. $P_{B,i}$ is the average downlink power dedicated to user i by the BS and $B_C N_0$ is the noise power and B_C is the bandwidth of a carrier utilized by the BS to deliver the content to user i.

When multiple wireless interfaces of a selected device is utilized for CCD (based on device selection method as explained in the next section) by the BS, the selected device first downloads a part of the content using its cellular interface, and then using its WiFi interface it broadcasts the same received content part to the other users which are within its vicinity. The selected device receives the content using the cellular interface so its instantaneous rate at the time instant t is also given by Eq. (1).

The success of receiving the content via WiFi link depends on the channel conditions between a selected broadcasting user and the receiving user. We consider that each selected device has a coverage radius of ρ_S. If a user is within the coverage radius of any selected device, the data content segment can be successfully received. Moreover, the WiFi channel on which selected users broadcast can be shared by other independent active users or access points which in turn can lead to uncoordinated competition for channel access and also may lead to interference among users. To take this into account, we evaluate the performance of the considered CCD methods for two different scenarios: 1) When there is no other independent active user or access point on the WiFi channel which is used by the selected user; and 2) When other independent active users or access points are also using the same channel as a selected device. For simplicity, we consider that the other competing WiFi users are fully saturated. In such scenarios, a selected device can still expect to get its 'fair share' $\frac{1}{A_c+1}$ of the airtime when it is contending with the competing user, where A_c is the number of other independent competing WiFi users on the same channel as the selected user (see [27] for details where channel access share of WiFi users under fully saturated scenario is studied).

To take into account the impact of interference from independent WiFi users in the cellular cell, we consider that there are X WiFi hotspot regions, where X varies between 1 to 4, and in each region there are O active WiFi users. Please note that this is reasonable as WiFi users in general are distributed in clusters. For example in a university campus, apartment building, etc. Each cellular cell can have multiple such clusters/regions. The instantaneous rate of a device that receives content via WiFi interface at time t is given by

$$R_{W,j}(t) = B_W \log_2 \left(1 + \frac{h_{ij}(t) P_{W_t,i}}{B_W N_0}\right) 1_i(t) \quad (2)$$

where $1_i(t)$ is an indicator function that is 1 if $d_{ij} \leq \rho_S$, for any $i \in \mathcal{N}_c$, and the user i successfully utilizes the medium when it shares the medium with A_c other users (otherwise it is 0), B_W is the bandwidth of the WiFi channel that is utilized by a selected device i, $P_{W_t,i}$ is the average WiFi power dedicated by sender i to a recipient j, $h_{ij}(t) = \frac{\kappa g_f(t)}{(d_{ij}^{\alpha})}$ is the channel gain with κ being the path loss constant, α the path loss exponent, d_{ij} the distance between the ith selected device and the receiving user j, $g_f(t)$ is the instantaneous fading gain, $B_W N_0$ is noise power and $\mathcal{N}_c$ is the set of selected users.

C. Performance Evaluation Metrics

In this subsection, we present the metrics that are used for performance evaluation of the proposed method.

1) Savings in terms of Cellular Carriers Utilized : Lets consider that N users are interested in the same content file. We perform simulations using I_N Monte Carlo runs for CCD using different methods. $N_{D,i}$ is the number of carriers utilized in the ith Monte Carlo run by the cellular BS when it delivers the content to selected users directly whereas the remaining users receive the content via their WiFi interfaces. Then average savings in the number of carriers per content file at the BS is given as

$$N_S = N - \frac{\sum_{i=1}^{I_N} N_{D,i}}{I_N}. \quad (3)$$

2) Bit-per-Joule Performance: The average bit-per-Joule performance of a user when the cellular BS delivers a content file directly to the N users is given as

$$J_C = \frac{1}{N} \sum_{i=1}^{N} \frac{R_{C,i}}{P_{C,i}}, \quad (4)$$

where $R_{C,i}$ is the average rate when user i receives the content by the BS and $P_{C,i}$ is the average power consumed by user i when receiving the content by the BS. The average bit-per-Joule performance of a user when the cellular BS delivers the content to the N_D users directly whereas $N - N_D$ users receive the content via WiFi interface is given as

$$J_S = \frac{1}{N_D} \left(\sum_{i \in \mathcal{N}_D} \frac{R_{C,i}}{P_{C,i}} \right) + \frac{1}{N - N_D} \left(\sum_{i \in \mathcal{N} \setminus \mathcal{N}_D} \frac{R_{W,i}}{P_{W_r,i}} \right), \quad (5)$$

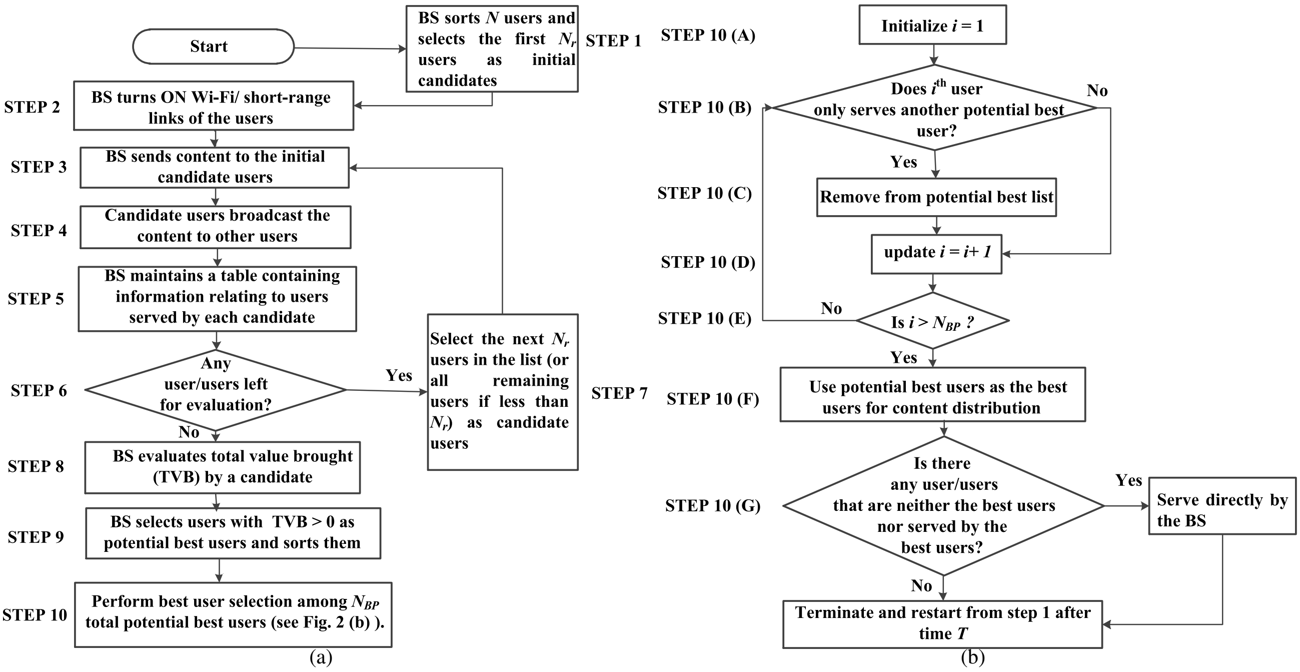
where $\mathcal{N}_D$ is the set of users to whom the cellular BS delivers the content directly, $R_{C,i}$ is the average rate when user i receives the content by the BS and $P_{C,i}$ is the average power consumed by user i when receiving the content by the BS, $R_{W,i}$ is the average WiFi rate of a user i, $P_{W_r,i}$ is the average power consumed by user i when receiving the content by WiFi.

3) Average Energy Cost: The average energy consumed to download a content segment of size S when the cellular BS delivers the content file directly to the N users is given as

$$E_N = \frac{S}{N} \left(\sum_{i=1}^{N} \frac{P_{C,i}}{R_{C,i}} \right). \quad (6)$$

The average energy consumed to download a content segment of size S when the cellular BS delivers the content to the N_D users directly, and the $N - N_D$ users receive the content via WiFi interface is given as

$$E_S = \frac{S}{N_D} \left\{ \sum_{i \in \mathcal{N}_D,} \left(\frac{P_{C,i}}{R_{C,i}} + \frac{P_{W_t,i}}{R_{W,i}} \right) \right\} + \frac{S}{(N - N_D)} \left(\sum_{i \in \mathcal{N} \setminus \mathcal{N}_D} \frac{P_{W_r,i}}{R_{W,i}} \right). \quad (7)$$



(a) (b)

Fig. 2: The select best method for selection of best content delivery devices.

D. Asymmetric Energy Consumption and Limited Battery of Devices

In the scenarios where the best devices out of the total N devices are selected by a BS for CCD, a user can be in one of the following operating modes.

- Default mode: In CCD, there are users which are chosen neither as selected nodes nor as recipient nodes, probably due to their location and/or poor link conditions. Such nodes download the content directly from the BS.
- Selected mode: The BS selects a subset of users applying the proposed method for CCD (see the next section for details) that requires these users to contribute their battery resources in broadcasting the same content to other users. Selected users expend their battery energy on receiving the desired content through their cellular link with the BS. The users also expend their battery energy in broadcasting the same content using WiFi. Hence, the average energy consumption for a user when it is in selected mode is greater than when it is in default mode. However, the average rate obtained by a user when it is in the selected mode is equal to the average rate obtained when it is in the default mode.
- Recipient mode: In CCD there are users which receive broadcasted content from the selected nodes via their WiFi interface. The recipient users expend their battery energy in receiving the desired content via WiFi interface. As shown in many measurement papers (which were discussed in Section II) that WiFi outperforms cellular interface in terms of average energy and rate, hence, the average energy consumption for a user when it is in the recipient mode is less than when it is in the default mode. Moreover, the average rate obtained by a user in recipient mode is higher than the average rate obtained by the user in the default mode.

As the energy consumed and the rates obtained by a user involved in CCD using multiple interfaces are different in the default, selected and recipient modes, it is useful (especially for intuitive purposes) to have rate obtained and energy consumed due to a method in terms of traditional default cellular method, i.e., the ratio of two energy or rate values. It is common to use relative values in wireless research (see [28]–[30]). We denote e_i^C, e_i^R, and e_i^N to represent the relative energy costs incurred by a user i being a selected, recipient, and default mode user, respectively. Similarly, r_i^C, r_i^R, and r_i^N are used to represent the relative rates obtained by a user i being a selected, recipient, and default mode user, respectively. When user i is in the selected mode, the relative energy cost for user i is given as

$$e_i^C = -\frac{E_{C,i}}{E_{C,i}} - \frac{E_{W_t,i}}{E_{C,i}} = -1 - \frac{E_{W_t,i}}{E_{C,i}}, \tag{8}$$

where $E_{C,i}$ is the average energy cost incurred by user i when it is given content directly by the BS through the cellular interface and $E_{W_t,i}$ is the average energy cost incurred by user i when it broadcasts content through the WiFi interface.

The relative rate for user i in the selected mode is expressed as

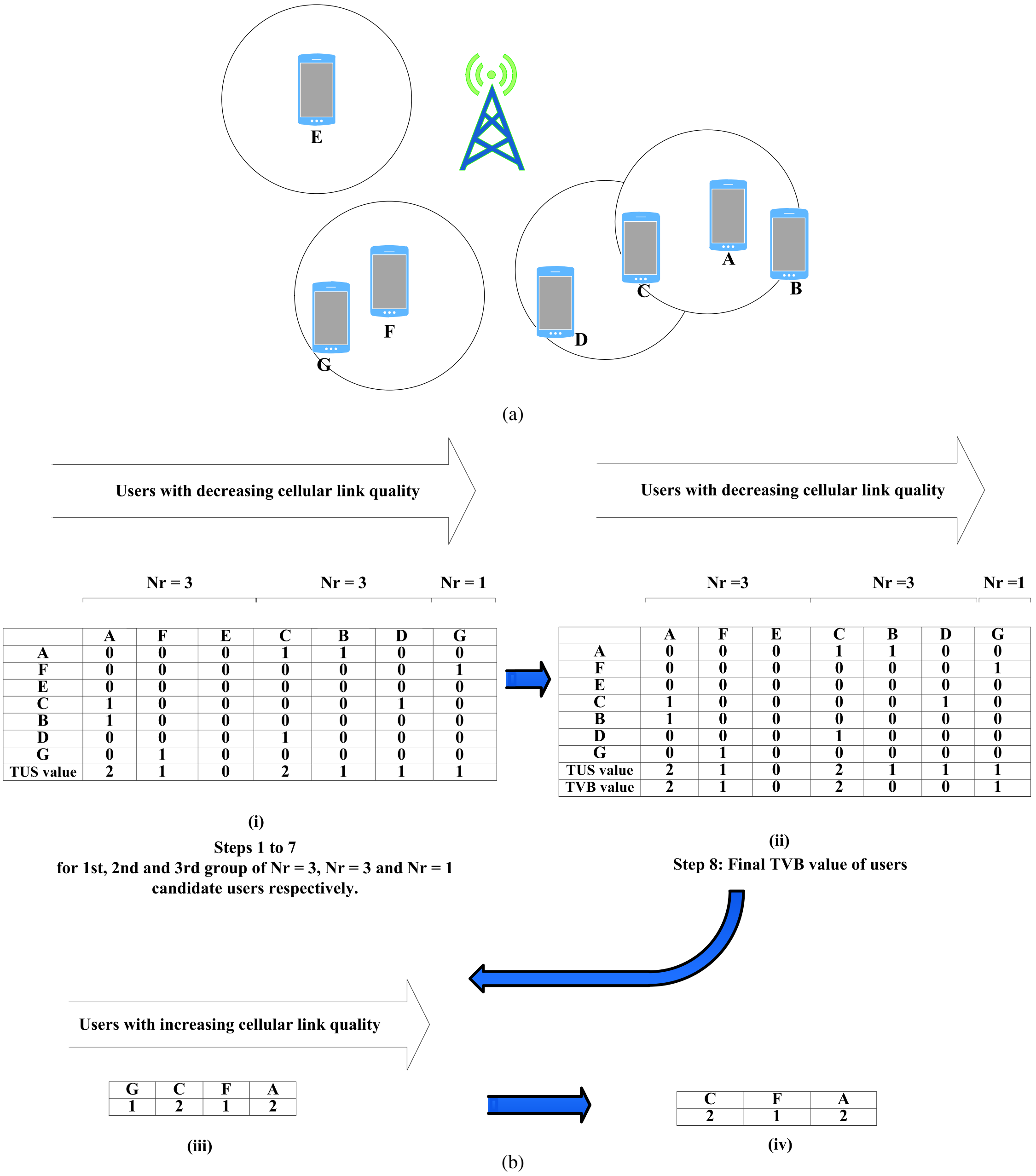
$$r_i^C = \frac{R_{C,i}}{R_{C,i}} = 1. \tag{9}$$

When user i is in the recipient mode, the relative energy cost is given as

$$e_i^R = -\frac{E_{W_r,i}}{E_{C,i}}, \tag{10}$$

where $E_{W_r,i}$ is the average energy cost when user i receives the broadcasted content through the WiFi interface; and the relative rate for user i in the recipient mode is expressed as

$$r_i^R = \frac{R_{W,i}}{R_{C,i}}, \tag{11}$$



(a)

	A	F	E	C	B	D	G
A	0	0	0	1	1	0	0
F	0	0	0	0	0	0	1
E	0	0	0	0	0	0	0
C	1	0	0	0	0	1	0
B	1	0	0	0	0	0	0
D	0	0	0	1	0	0	0
G	0	1	0	0	0	0	0
TUS value	2	1	0	2	1	1	1

(i)

Steps 1 to 7
for 1st, 2nd and 3rd group of Nr = 3, Nr = 3 and Nr = 1
candidate users respectively.

	A	F	E	C	B	D	G
A	0	0	0	1	1	0	0
F	0	0	0	0	0	0	1
E	0	0	0	0	0	0	0
C	1	0	0	0	0	1	0
B	1	0	0	0	0	0	0
D	0	0	0	1	0	0	0
G	0	1	0	0	0	0	0
TUS value	2	1	0	2	1	1	1
TVB value	2	1	0	2	0	0	1

(ii)

Step 8: Final TVB value of users

G	C	F	A
1	2	1	2

(iii)

C	F	A
2	1	2

(iv)

(b)

Fig. 3: a) An example topology scenario in which 7 users are interested in the same content in the cellular coverage of a base station. b) How the Select Best method selects users for CCD using multiple interfaces for the considered example scenario.

where $R_{W,i}$ is the average WiFi rate of a user i.
When a user i is in the default mode (neither in the selected mode or in the recipient mode), its relative energy cost is given as

$$e_i^N = -\frac{E_{C,i}}{E_{C,i}} = -1. \tag{12}$$

Its relative rate in the default mode is expressed as

$$r_i^N = \frac{R_{C,i}}{R_{C,i}} = 1. \tag{13}$$

IV. PROPOSED SELECT BEST (SB) METHOD, ITS COMPLEXITY, AND SELFISH DEVIATIONS

In this section, we present our SB method for the selection of best wireless content delivery devices, and also discuss the impact of the presence of selfish users in the network.

A. Select Best Method

The proposed method is described in Fig. 2 and the steps involved in the proposed method are given below. Moreover, we also provide an example scenario in Fig. 3, and illustrate different steps of the presented method for the considered example.

- Step 1: The BS sorts N users in terms of decreasing cellular link quality and selects the first N_r users to evaluate as possible candidates for content delivery. In our work we consider the data rate as a measure of the quality of a communication link between the mobile station and the cellular base station. Note that the number N_r of candidate users that are utilized for selection in each round depends on the user density. For a large number of N users, N_r can be taken as higher but for small to medium values it is kept small.

- Step 2: The short-range/WiFi link of the users are turned on by the BS. As a cellular network can have information about which users in a cell are interested in the same content it is essential that a base station controls WiFi interface of users, as it can increase the battery life on a mobile device by turning off the interface when there are no users available for cooperative content delivery near its vicinity. In [31], [32] methods and software based solutions are proposed in which the mobile device's WiFi interface is enabled/disabled by a BS when the device can be engaged/not engaged. When a device does not support the WiFi interface the BS always utilizes the default cellular connection.
- Step 3: The BS delivers a content segment (packets) to the selected candidate users.
- Step 4: The candidate users broadcast the received content through WiFi links while the other users listen.
- Step 5: The BS maintains a table containing served user and the number of total users served (TUS) by each candidate as follows: Each served user sends to the BS the number of packets received (successfully) from a candidate user. Along with this, it also sends the candidate users' DEV-ID such as MAC address to identify the candidate user and also to distinguish between the numbers of packets successfully sent by more than one candidate users, if any as a user can receive packets from more than one candidate user, if it is in the vicinity of all of them. The BS maintains a table for candidates in the network in which when a user is successfully served by a candidate it is given a value of 1; otherwise 0. Moreover, the BS also stores the total number of users (TUS) served by a candidate (by summing all the 1's).
- Steps 6 and 7: The process is repeated for the next round of candidate users, if any.
- Step 8: The BS evaluates the total value brought (TVB) by a candidate user as follows: Initially TVB = TUS value, the BS sequentially evaluates each candidate to check if a candidate user is serving another user/users that is/are already served by another user. If a user is already served by another user the BS decreases the TVB value of this candidate user. In other words since the candidate user is serving an already served user it does not brings any additional benefit in terms of content distribution, and hence its value is decreased. Moreover, due to overlapping coverage, if a user receives the same packets from two different candidate users this can increase overhead in terms of energy and delay.
- Step 9: The BS selects the candidate users with TVB > 0 as the potentially best candidate (N_{BP}) users. It then sorts these users in terms of increasing cellular link quality.
- Step 10: The BS then checks that if any of the potentially best candidate users is only serving another potentially best candidate user, if yes, then it is removed from the list of selected users as this potentially best candidate user brings no additional value since it is serving another potentially best candidate user that is already served by the cellular link directly. Otherwise, the potentially best candidate user is chosen as the selected user. This process is repeated over all the potentially best candidate users. In this way, a group of selected users is decided to broadcast content. Finally, the BS checks if there is any user that is neither a selected user nor a recipient user. If there is any such user, the BS delivers the content directly to that user.

To incorporate changes in the interference environment and/or user distribution the process of evaluation of selected users is re-initiated after some time T. This time T may be assigned according to variations in the interference environment or changes in the user distribution. While performing selection the SB method takes into account the quality of a communication link between a mobile station and a cellular base station, the quality of WiFi link among the mobile station and users in its vicinity, and how many users it serves. Although, the probability of two mobile devices having the same cellular and the WiFi link qualities, and serving the same users is low, but when they have the method selects one device out of them randomly.

We next consider the complexity of the proposed method: Step 1 involves sorting the users and hence requires $O(N\log_2 N)$ operations. Step 2 requires $O(N)$ operations. Steps 3 to 7 are repeated and they involve first sending content segment to each of $N_r < N$ candidate users, then each candidate user broadcasts the content segment independently, and finally the BS stores for each candidate its TUS value, in total there are $O(\lceil \frac{N}{N_r} \rceil (N_r + N_r + N_r N))$ operations. Step 8 involves N operations for each user and it requires $O(N^2)$ operations. Step 9 involves N operations as the BS checks for each user whether its value is greater than 0, and hence it requires $O(N)$ operations. Step 10 involves n operations, where $n < N$ is the number of potentially best users, for each potentially best user, and it requires $O(n^2)$ operations.

B. The SB method and selfish users

CCD using the SB method requires users of selected devices to contribute their resources. A key challenge faced in the design of efficient CCD methods is that portable wireless devices have limited energy as they are battery powered. In our proposed SB method, although the cellular BS assists in CCD, each mobile user is an independent entity who acts to maximize its own utility and can deviate from the proposed CCD method if a deviation could increase its utility. In other words, the SB method can be vulnerable to free-riding users. One such example of free-riding in the SB method can be when some users when chosen as recipients, receive the broadcasted content from the other selected users but are not willing to contribute their own resources when they are selected to broadcast content to the other users. This motivates us to analyze the stability of the proposed SB method using the framework of repeated games. The framework of repeated games provides useful tools to study selfish behavior among

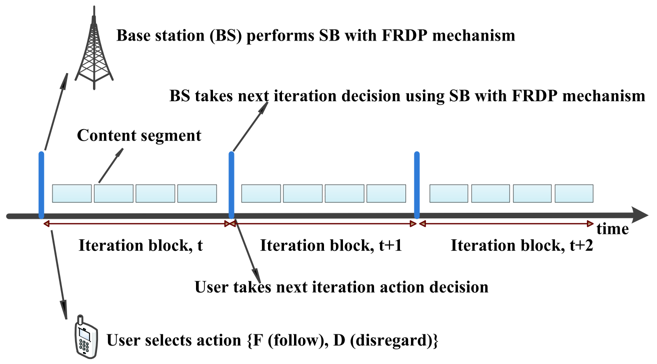


Fig. 4: CCD using best devices operation across multiple iterations (rounds).

CCD users that interact repeatedly over time to participate in content distribution [33], [34]. As the CCD users are unsure about when precisely their interactions with the other users will end, the model of repeated games with an infinite time horizon can be used to analyze such situations.

V. GAME THEORETIC FORMULATION OF CCD USING BEST DEVICES AND ITS ANALYSIS

The CCD game using the best devices in a strategic form is specified by a 3-tuple $G = \langle \mathcal{N}, \mathcal{A}_i, U_i \rangle$, where

- $\mathcal{N}$ is a set of users that are interested in the same content within a macro-cell.
- A set of actions, $\mathcal{A}_i = \{F, D\}$, for each user $i \in \mathcal{N}$, that are taken when a user is either chosen as a selected mode or a recipient mode node. F represents the action that a user cooperatively *follows* the BS selection, and D represents the action that a user *disregards* the BS selection decision. The set of actions together define a set of possible action profiles $\mathbb{A} = \times_{i \in \mathcal{N}} \mathcal{A}_i$ and $\mathbf{a} = (a_1, a_2, \cdots, a_N)$ denotes a strategy profile of all users.
- A utility function for each user i

$$U_i = p_{c,i}\big(w_1 e_i^C + w_2 r_i^C\big) + p_{r,i}\big(w_1 e_i^R + w_2 r_i^R\big) + p_{n,i}\big(w_1 e_i^N + w_2 r_i^N\big), \tag{14}$$

  where
    - $p_{c,i}$ and $p_{r,i}$ represent the probabilities of a user being in the selected mode and in the recipient mode, respectively. $p_{n,i}$ represents the probability that user i is in the default cellular mode, where $p_{n,i} = (1 - p_{c,i} - p_{r,i})$.
    - e_i^C, e_i^R, and e_i^N, represent the relative energy costs incurred by user i (see Eqs. (8-13));
    - r_i^C, r_i^R, and r_i^N represent the relative rates obtained by a user; and
    - w_1 and w_2 are user i's preference weights of metrics, where $w_1 + w_2 = 1$. The choice of weights w_1 and w_2 may depend on the particular device's battery condition. For instance, for a user with a low battery level, the higher energy cost may be more important than the obtained rate. As a result, the higher weight may be assigned to the energy part of the utility as compared to the rate part.

In the infinitely repeated game model of CCD using best devices, the *stage game* G is played at each round k, where in each round content segments of the requested content are delivered. We consider that the users make decisions rationally to maximize their long-term expected utilities. Practically it is difficult for an independent user operating in a cellular network to know on its own: 1) Who wants the same content as the user? 2) Where that user is located? 3) What is that user's link quality? 4) When that user wants to cooperate. Moreover, a user that is currently involved in CCD with a user/group of users may have to later involve in CCD with some other user/group of users. In other words, users participating in the CCD using multiple interfaces are unsure about when precisely their interactions should start/end. The model of repeated games with an infinite time horizon is used to analyze such situations. There are different ways in which a preference relation may be modeled in an infinitely repeated game. In this paper, we have used Limit of means which is one of the main one. The average utility per round of user i is given by

$$V_i = \lim_{\bar{T} \to \infty} \frac{1}{\bar{T}} \sum_{k=1}^{\bar{T}} U_i^k, \tag{15}$$

Next we establish the condition under which following the BS's selection, i.e., playing the action F, yields a higher average utility as compared to when each user downloads the content directly through an individual BS carrier.

Under the traditional method, where every user downloads content directly through a BS carrier, then in Eq. (14), $p_{c,i} = 0$, $p_{r,i} = 0$, and $p_{n,i} = 1$. The average utility of user i is independent of the actions of other users and in this case the average utility is given as $U_i = w_1 e_i^N + w_2 r_i^N$. Note that for this case when $w_1 = w_2$ then $U_i = -1/2 + 1/2 = 0$, as $e_i^N = -1$ and $r_i^N = 1$. Under the proposed SB method when all users play F, i.e., $U_i(a_i, a_{-i}) = U_i\big(F, (F, F, \cdots, F)\big)$, in each round then using Eq. (14), the average utility for each user i in each round is

$$\begin{aligned} U_i(a_i, a_{-i}) =& U_i\big(F, (F, F, \cdots, F)\big) \\ =& p_{c,i}\left\{ w_1\left(-1 - \frac{E_{W_t,i}}{E_{C,i}}\right) + w_2 \right\} + p_{r,i}\left\{ w_1\left(-\frac{E_{W_r,i}}{E_{C,i}}\right) \right. \\ & \left. + w_2\left(\frac{R_{W,i}}{R_{C,i}}\right) \right\} + p_{n,i}\left(-w_1 + w_2\right). \end{aligned} \tag{16}$$

The negative values are used for the relative energy costs as the utility function proposed in Eq. (16) is a weighted sum of rewards and costs, where the rewards are the relative rates obtained and the costs are the relative energy consumed under different scenarios. To ensure that playing the action F, i.e., cooperating and following the BS selection in each round, yields a higher average utility as compared to when all the users download the content directly through a BS carrier, the average utility of each user when they play F should be greater than the utility that users can obtain when they download content directly through the BS carrier, i.e.,

$$U_i\big(F, (F, F, \cdots, F)\big) > -w_1 + w_2. \tag{17}$$

For $w_1 = w_2 = \frac{1}{2}$, by solving inequality (17), we obtain

$$\frac{p_{c,i}}{p_{r,i}} < \left(\frac{R_{W,i} E_{C,i} - E_{W_r,i} R_{C,i}}{R_{C,i} E_{W_t,i}} \right). \tag{18}$$

In other words, to ensure a higher utility due to cooperation, for each user i the ratio of probability of being served in the selected mode to the probability of being served in the recipient mode, i.e., $\frac{p_{c,i}}{p_{r,i}}$, must satisfy inequality (18). Next we provide intuitive explanation of inequality (18) by setting different values for relative rates and energy. We consider the following examples: 1) When average WiFi rate is twice as the average cellular rate, average energy consumed in transmitting content for a user in the selected mode using WiFi interface is twice as much as average energy consumed in receiving the same content by cellular interface, and the average energy consumed in receiving content for a user in the recipient mode using WiFi interface is half as much as energy consumed in receiving the same content by cellular interface. In this case, using inequality (18), $\frac{p_{c,i}}{p_{r,i}} < 0.75$. This means that for a user using the SB method, higher utility as compared to the utility obtained using the default cellular mode for a user can only be maintained when a user is more often in the recipient mode as compared to the selected mode. 2) When the energy values are the same as in the previous example but the WiFi rate is five times as cellular rate then $\frac{p_{c,i}}{p_{r,i}} < 2.25$. This means that using the SB method, a higher utility can now even be maintained when a user more often serves as selected user as compared to a recipient. It is important to note that due to the broadcast nature of WiFi links a single user in the selected mode may be able to serve many recipients. The proposed SB method only selects a user to be in the selected mode when there is at least one recipient in its vicinity that can receive the content. Since in our model all users are treated equally, hence under the proposed method $\frac{p_{c,i}}{p_{r,i}} \geq 1$. Before presenting further results we next make the following observation.

Remark A deviation where user i plays action D when it is selected by the BS as a recipient is inefficient for that user. This follows from the fact that the average energy cost is less and the average data rate is higher when user i receives content on its WiFi interface as compared to when it receives content directly from the cellular interface (as discussed earlier in Section II). Moreover, using our proposed SB method, a user is selected as a recipient only when a user with good WiFi link to the recipient is present in its vicinity. This ensures that only those WiFi links are utilized for cooperation that have good link quality. A user can never guarantee that with low energy consumption it can download content segments via WiFi interface as wireless performance of any user's WiFi link changes due to many variables. For example, due to interference on the user's WiFi channel maintaining a connection to the other users in its vicinity can be difficult, in which case the user will drop content segments. Moreover, interference can also affect the speed of the wireless content reception, in which case the user will consume more energy to download the content segments. In such scenarios, if the user is using a low cellular link device then it will have no choice but to utilize its low WiFi link for download and incurs loss in performance. Moreover, a user can also never guarantee that there is another user within its WiFi coverage that has the same content as the user. When there is no other user within its coverage it needs to download content via cellular link and using a low cellular link device can result in severe performance loss.

The deviation from the proposed method that we need to consider is that deviation where a user i is to serve as a selected mode user and it plays D. In this case by disregarding the BS selection, the user i can save its energy costs that are incurred in broadcasting the content via its WiFi interface. Next we show that in the proposed game the strategy profile where all users follow the SB selection i.e., play F in each round, $\mathbf{a} = (F, F, F, \cdots, F)$, is not a Nash equilibrium (NE).

Proposition 5.1: In the proposed game, the strategy profile where all users follow the SB selection i.e., play F in each round, $\mathbf{a} = (F, F, F, \cdots, F)$, is not a Nash equilibrium (NE).

Proof: When all users follow SB method selection, the outcome will be cooperation in each round, whose average utility per round for a user i is $U_i\big(F, (F, F, \cdots, F)\big)$ (given in Eq. (16)).

Consider the unilateral deviation where user i plays D in each round when it is chosen to be in the selected mode, otherwise it plays F, whereas all the other users play always F. Since all other users follow the SB method, user i will obtain the same average utility, as before, in the rounds where it is in the recipient mode and also where it is neither in the recipient nor in the selected mode. However, in the rounds where user i is in the selected mode, user i can now save its energy costs that are incurred in broadcasting the content via its WiFi interface. The average utility per round for user i now is

$$\begin{aligned} U_i\big(D, (F, F, \cdots, F)\big) =& p_{c,i}\big(-w_1 + w_2\big) + p_{r,i}\big(w_1 e_i^R + w_2 r_i^R\big) \\ &+ p_{n,i}\big(-w_1 + w_2\big), \\ =& p_{c,i}\big(-w_1 + w_2\big) + p_{r,i}\Bigg\{ w_1 \left(-\frac{E_{W_r,i}}{E_{C,i}}\right) \\ &+ w_2 \left(\frac{R_{W,i}}{R_{C,i}}\right)\Bigg\} + p_{n,i}\big(-w_1 + w_2\big). \end{aligned} \tag{19}$$

It is easy to see that $U_i\big(D, (F, F, \cdots, F)\big) > U_i\big(F, (F, F, \cdots, F)\big)$, which proves our claim. ■

Proposition 5.1 shows that the proposed method is vulnerable to free-riding users and poses a "tragedy of the commons" dilemma [8]. This implies that if too many users exploit others' WiFi interfaces for content delivery, the excess of free-riders drives away the cooperating users that make the cooperation viable. Next, we present a carrier aggregation based incentive mechanism for the SB method that allows users to cooperate and obtain a higher utility. We also show that under the proposed incentive mechanism following the SB method is a Nash equilibrium.

VI. THE PROPOSED CCD GAME WITH CARRIER AGGREGATION BASED INCENTIVES

The characteristics of the proposed CCD method present unique challenges and opportunities for the design of novel incentive and punishment mechanisms to ensure CCD. This is due to the reason that straight forward applications of well-known direct and indirect reciprocity mechanisms for incentivizing cooperation and punishing defections among users (some of which were reviewed in Section II) may not be effective in the context of the proposed method. For instance, due to changes in cellular network topology, users involved in CCD changes over a period of time. A user that is currently involved in CCD with a user/group of users may have to later involve in CCD with some other user/group of users. Hence, very often a user may have no opportunities for direct/indirect incentivization, or retaliation in response to free-riding, as user interactions change over a period of time. Moreover, in

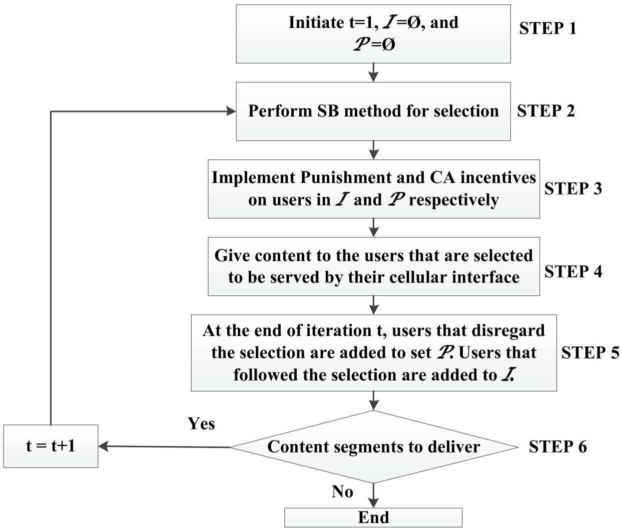


Fig. 5: Flow diagram of the FRDP incentive strategy

practice it is memory and computation intensive to follow a reciprocity based protocol that requires each user to observe and keep track of identities, strategies and reputation of different users with which they interact over a period of time. To avoid such memory and computation intensive operations on a user's device, we next present a method in which the BS implements the Follow-Reward and Disregard-Punish (FRDP) incentive and punishment mechanism to discourage the users from the free-riding behavior. The BS and a user decision making processes are illustrated in Fig. 4.

A. The SB Method with FRDP Mechanism

The flow diagram of the steps involved in the FRDP mechanism is given in Fig. 5.

- Step 1: Initialize the iteration ($t = 1$), initialize $I = \emptyset$, the set of users in carrier aggregation (CA) incentive group, and initialize $\mathcal{P} = \emptyset$, the set of users in punishment group.
- Step 2: The BS performs user selection applying the SB method in the beginning of every iteration t. We define an iteration t as a block of content segment delivery periods of fixed duration during which the BS does not change the selection of users, and the users do not change their actions.
- Step 3: After performing selection, the BS checks whether a user selected to be in the recipient mode is in the set $\mathcal{P}$. If yes, the BS punishes the user for the entire iteration block in the following ways. In the given iteration, if the user is selected to be served via WiFi interface, the BS punishes the user by delivering content to it through its cellular interface with a single carrier. In the given iteration, if the user is selected to be served via cellular interface then no CA is employed for the user. After the iteration, in which the user is punished by being served with a single cellular carrier when it was supposed to be served via the user's WiFi interface, the user is removed from the set $\mathcal{P}$.

  When the user is selected to be delivered content via cellular link and it is in the set I, the BS then incentivizes the user for the entire iteration block. The BS aggregates the user's default cellular carrier with additional carriers that are saved due to the other recipient users receiving content via WiFi link. The BS then removes it from the set I.
- Step 4: The BS delivers the content to the users that are to be served by their cellular interface.
- Step 5: The BS checks if the selected users followed the selection in the current iteration.
- Step $5(a)$: If a user follows the selection it is added to the set of users I. Step $5(b)$: If the selected user disregards the selection by the BS , then it is removed from the set I and is added to the set $\mathcal{P}$.
- Step 6: The steps 2 till 5 of the FRDP strategy are repeated till the requested content is delivered to the users.

Under the proposed FRDP mechanism when all users always follow the SB method selection, the average utility of user i is given as:

$$\begin{aligned}
U_i^{FRDP}\big(F,(F,F,\cdots,F)\big) =& p_{c,i}\big(w_1\hat{e}_i^C + w_2\hat{r}_i^C\big) + p_{r,i}\left(w_1\hat{e}_i^R + w_2\hat{r}_i^R\right)\\
&+ p_{n,i}\big(w_1\hat{e}_i^N + w_2\hat{r}_i^N\big),\\
=& p_{c,i}\left\{w_1\left(-\frac{\hat{E}_{C,i}}{E_{C,i}} - \frac{E_{W_t,i}}{E_{C,i}}\right) + w_2\left(\frac{\hat{R}_{C,i}}{R_{C,i}}\right)\right\}\\
&+ p_{r,i}\left\{w_1\left(-\frac{E_{W_r,i}}{E_{C,i}}\right) + w_2\left(\frac{R_{W,i}}{R_{C,i}}\right)\right\}\\
&+ p_{n,i}\left\{w_1\left(-\frac{\hat{E}_{C,i}}{E_{C,i}}\right) + w_2\left(\frac{\hat{R}_{C,i}}{R_{C,i}}\right)\right\},
\end{aligned} \tag{20}$$

where

- $\hat{e}_i^C$, $\hat{e}_i^R$, and $\hat{e}_i^N$ represent the relative energy costs incurred by user i being chosen as a selected mode, a recipient mode and a default mode user, respectively, when there are CA incentives. All energy costs are defined relative to the energy costs when the user is given content only using the default cellular mode;
- $\hat{r}_i^C$, $\hat{r}_i^R$, and $\hat{r}_i^N$ represent the relative rates obtained by a user being a selected, recipient and default user, respectively, when there is CA incentive. All rates are defined relative to the obtained rates when the user is given content only using the default cellular mode; and
- $\hat{E}_{C,i}$ represents the average energy cost and $\hat{R}_{C,i}$ represents the average rate of user i when the user is given content directly by the BS through the cellular interface using CA.

To ensure that playing the action F yields a higher average utility as compared to when the users download the content directly through a BS carrier, it is required that $U_i^{FRDP}\big(F,(F,F,\cdots,F)\big) > -w_1 + w_2$. Earlier in Section V we showed that when WiFi rate is twice the cellular rate, the SB method (with no FRDP incentive mechanism) ensures a higher utility only when a user more often serves as a recipient user as compared to it serves as a selected user. By setting the same relative values in the above inequality, as the values used in Section V for inequality (18), it can be seen that $p_{c,i} < 0.55p_{r,i} + 0.20$. In other words, for the same considered scenario using the SB method with FRDP incentive mechanism, for $p_{c,i} < 0.20$ the user i can obtain higher utility as compared to the default cellular mode even when $p_{r,i} = 0$.

Proposition 6.1: In the proposed CCD game, when the SB method with the FRDP incentive mechanism is used for CCD then the strategy profile where all users play F in each round, i.e., $\mathbf{a} = (F,F,F,\cdots,F)$, (and value $w_1 \leq w_2$), is a Nash equilibrium (NE).

Proof: When all users follow the SB method with FRDP incentive mechanism, the outcome will be cooperation in each round, whose average utility per round for user i is given in Eq. (20). To show that the strategy profile $(F,F,F,\cdots,F)$ is a Nash equilibrium, we need to consider a deviating user i, whereas all other users play F. In the proposed SB method with FRDP incentive mechanism, when the user i deviates in any given round then in the next few rounds (until the user is removed from the punishment group) the user can get punished in one of the following ways: a) In a round, if the user is selected to be served via WiFi interface, the BS punishes the user by delivering content to it through its cellular interface with a single carrier. b) In a round, if the user is selected to be served via cellular interface then no CA is employed for the user. After the punishment round in which the user is served with a single cellular carrier when it was supposed to be served via the user's WiFi interface, the user is then removed from the punishment group. To show that the SB method with FRDP mechanism is a Nash Equilibrium, we need to show that the sum of the obtained utilities in a deviating round and the subsequent rounds in which the user gets punished is less than the sum of the obtained utilities if the user has followed the strategy in the same rounds. Now, consider the deviation where the deviating user i plays F in the $\tau - 1$ rounds then plays D in the τth round when the user is selected to broadcast the content, and then again keep playing F for the remaining rounds, whereas all the other users always play F. The long time expected utility of user i is given as

$$\sum_{k=1}^{k=\tau-1} U_i^{FRDP}\big(F,(F,F,\cdots,F)\big) + U_i^{FRDP}\big(D,(F,F,\cdots,F)\big) + \sum_{k=\tau+1}^{\infty} U_i^{FRDP}\big(F,(F,F,\cdots,F)\big). \tag{21}$$

The average per round utility of each of other users that play F in every round is given in Eq. (20). The average per round utility of the deviating user that plays F in the first $\tau - 1$ rounds is the same as of other users (given by Eq.(20)). In the τth round the deviating user gains in utility by not delivering the content via WiFi interface, the average payoff for the deviating user i in the τth round is

$$U_i^{FRDP}\big(D,(F,F,\cdots,F)\big) = \left\{ w_1\left(-\frac{\hat{E}_{C,i}}{E_{C,i}}\right) + w_2\left(\frac{\hat{R}_{C,i}}{R_{C,i}}\right) \right\}. \tag{22}$$

In the next round, i.e., $(\tau + 1)$th round, the BS punishes the user and the user's utility in each of the next few rounds (until the user is removed from the punishment group) is $-w_1 + w_2$. Let us consider the best possible case for the deviating user i in which the user i after deviating is punished only for one round. This best case scenario happens, when after deviating, in the next round the user is selected as a recipient mode user and is served via cellular interface instead of WiFi interface, the user is then removed from the punishment group. For the two rounds, in which the user deviates in the first and gets punished in the second round, the average sum utility of the user is $\left[w_1\left(-\frac{\hat{E}_{C,i}}{E_{C,i}}\right) + w_2\left(\frac{\hat{R}_{C,i}}{R_{C,i}}\right) + \left(w_2 - w_1\right) \right]$. Instead of deviating, if the user had followed the strategy then the user's average sum utility would have been $\left[w_1\left(-\frac{\hat{E}_{C,i}}{E_{C,i}} - \frac{\hat{E}_{W_t,i}}{E_{C,i}}\right) + w_2\left(\frac{\hat{R}_{C,i}}{R_{C,i}}\right) + w_2\left(\frac{\hat{R}_{W,i}}{R_{C,i}}\right) - w_1\left(\frac{\hat{E}_{W_r,i}}{E_{C,i}}\right) \right]$. For the sceneraios where $w_1 \leq w_2$, it can be seen that the user saves energy in the first round when it deviates, however, due to punishment it loses in terms of both energy and rate in the second round, as it is not given content via WiFi interface. On average WiFi rates are higher than the cellular rates and also on average WiFi has less energy costs. Moreover, unlike the best case scenario discussed above, the deviating user can also get punished by not getting higher cellular rates via CA incentive, when it is selected as the default mode user. Hence, the average sum utility due to deviation is less than the average sum utility obtained when the user follows the strategy. In other words, there is no incentive in unilateral deviation, which proves our claim. ■

It is important to note that for the scenarios where $w_1 > w_2$, i.e., where users value energy more than their obtained rates, the proposed strategy is still Nash equilibrium when the difference between WiFi energy/rates and cellular energy/rates are much higher as compared to the difference between w_1 and w_2, and/or when the users can be given a higher number of carriers as CA incentives for CCD.

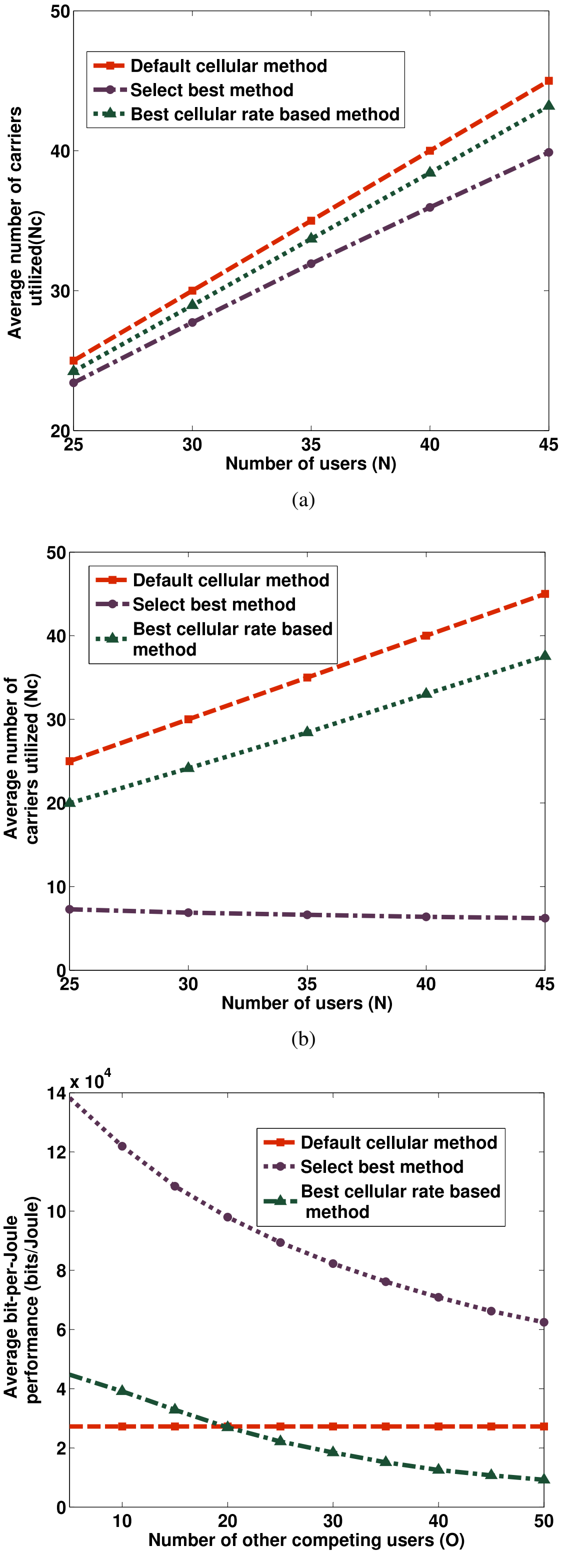
VII. SIMULATION RESULTS

A. Performance Analysis of the SB Method without Incentive Mechanism

We simulate a cellular cell of radius $\rho_T = 1$ km in which N users that are interested in the same content are: 1) Randomly deployed; and 2) Deployed in clusters (see Section III for the details of user distribution). User clusters are generated by (randomly) dropping circles of radius ρ_C in the cellular cell. We assume that the transmitting power of the BS is 43 dBm and the noise power is set to a value of -100 dBm. Path loss values of κ and α are set to 1 and 3, respectively. The transmit and receive power of each user terminal is 20 dBm. The noise power is assumed to be -40 dBm. The circular coverage region of each content delivery user (using WiFi link) is set to be 75 meters. The average cellular rates between the BS and a user are considered to be in the range of 600 Kbps to 2 Mbps. The average WiFi rates among the users are considered to be in the range of 5 to 40 Mbps. We compare the performance of the proposed method for wireless content delivery against the following methods: 1) When only cellular link is used to deliver content to all the users; and 2) When the cellular BS selects a subset of users (based on best cellular link) that cooperatively deliver content to the other users.

Note that the process of content distribution has only one stage for method 1, i.e., where the BS delivers data to all users, whereas in method 2 and in the proposed method the content distribution process has two stages, i.e., where the BS sends content to selected users (stage 1) via cellular link and then selected users broadcast data for other users via WiFi link (stage 2).

For analyzing the effect of other independent competing users (operating in the same WiFi channel) on the performance of the proposed method, we consider that O independent users

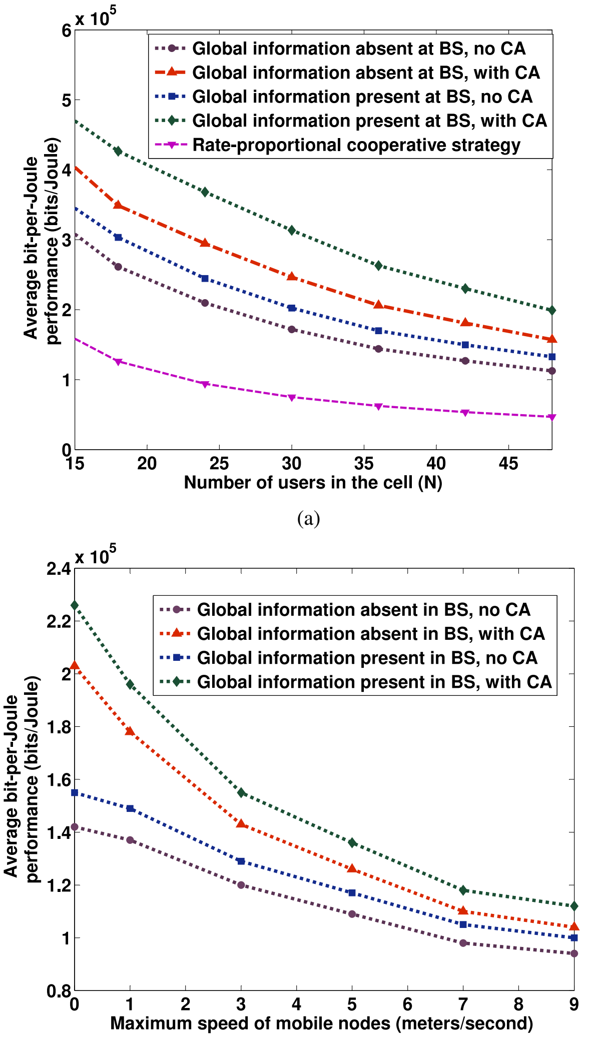


(a)

(b)

(c)

Fig. 6: (a) and (b) Number of carriers vs number of users when users are randomly distributed and cluster-wise distributed respectively; and (c) Average bit-per-Joule performance vs number of other competing users when the users are deployed in clusters.



(a)

(b)

Fig. 7: a) Average bit-per-Joule performance vs number of N users for different CCD methods; and b) Average bit-per-Joule performance vs maximum speed of a mobile user.

operate (see Section III for the details). The values of O are varied between 5 to 50.

1) Number of frequency carriers employed: In Figs. 6a and 6b, we plot the average number of frequency carriers used by the BS (to deliver content to N users) as a function of the number of N users in the network under two different user distributions (for three different methods).

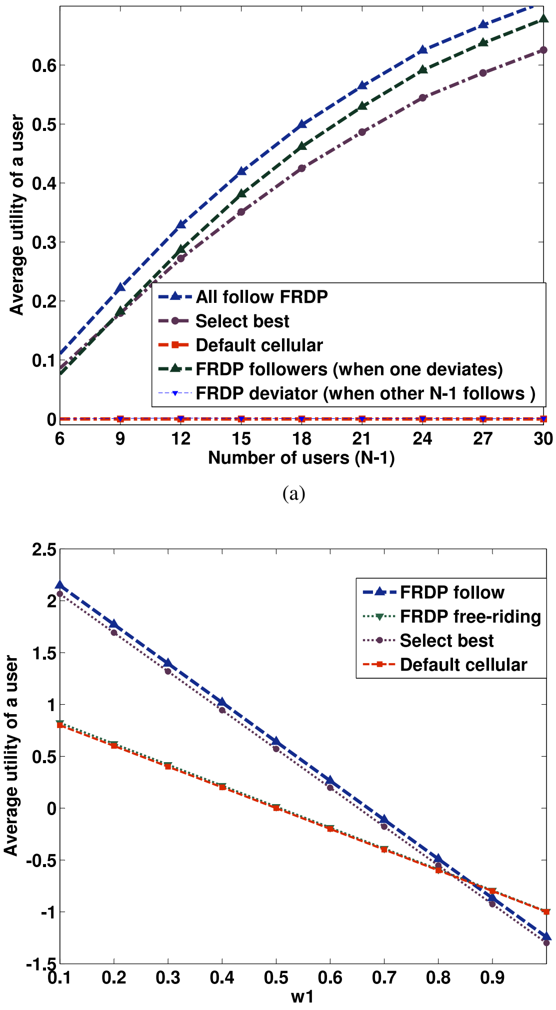
The two figures show that the method in which only cellular link is utilized to deliver the content to N users performs worst (in terms of number of carriers utilization). It can be seen in Fig. 6a that the proposed method has limited performance gain in terms of carrier savings when the active users are randomly distributed in the cell. However, Fig. 6b shows that the performance gain is significant when the same number of users have clustered distribution in the cell.

2) Average bit-per-Joule performance: In Fig. 6c, we present the average bit-per-Joule performance as a function of the number of other independent competing users in the cellular cell that utilize the same WiFi channel as the CCD devices. It can be seen that the proposed method achieves the highest bit-per-Joule performance as compared to the other two schemes when no other competing users are present on the WiFi channel. In the presence of other competing users, as expected, the conventional cellular method does not shows any change in performance. Although the performance of the proposed method degrades with increasing number of competing users, however, it still outperforms the other two methods. It can be also seen in Fig. 6c that when the number of other independent WiFi competing users is low than the best cellular rate based method performs better than the default cellular method in terms of average bit-per-Joule performance. However, as the number of other WiFi users increases, the performance of best cellular rate based method degrades as compared to the default cellular method as the default method is unaffected by other WiFi users.

B. Performance Analysis of the SB Method with the Incentive Mechanism

Using the same simulation parameters as used in Section VII-A, we now evaluate the performance of the SB method with the FRDP mechanism under different scenarios. In our simulations, we consider two different behaviors of selected users for CCD: i) a user always follows the BS selection; and ii) a user always free-rides, i.e., it disregards the BS selection when it is selected to broadcast the content to other users. We compare the performance of the proposed mechanism with the following other methods: 1) The method in which only cellular link is used to deliver content to all users in each iteration; 2) The SB method without FRDP mechanism; 3) The rate-proportional cooperative approach; and 4) An approach in which it is assumed that global network information (device coverage, link quality of interfaces) are available at the base station. The benefit of such comparison is that one can evaluate the energy consumed in the overhead relating to the best devices selection process.

In Fig. 7a, we present the average bit-per-Joule performance of different methods as a function of increasing number of users. We compare the performance of the proposed method with a rate-proportional cooperative approach where the content segments are split rate-proportionally at the base station and then different parts of the segment are downloaded by each device using their cellular interface. The received content segment parts are then cooperatively exchanged (using broadcasting) by users using their short-range/ WiFi interfaces [15], [35]. It can be seen that the rate-proportional cooperative method considered in different works perform less than the proposed solution. This is due to the reason that while our proposed solution utilizes best link devices for cooperative content delivery, the rate-proportional cooperative method utilizes all the devices and some of them can have poor link qualities. Moreover, the use of selected devices in our solution results in cellular carrier savings at the base station which are then utilized as carrier aggregation incentives for performing cooperative content delivery. This further increases the average-bit-per-Joule performance of the proposed method as compared to the rate-proportional cooperative method which utilizes all the links and cannot result in carrier savings. The figure also shows the loss in bit-per-Joule performance (due to the overhead relating to the best devices selection process) when compared with the global information method where user selection is assumed to be already known. The figure also shows that the performance of all the methods degrades with the increasing number of users. This is due to the reason that as the number of users increases, the possibility that users are within WiFi coverage range of other users also increases. As more users share the airtime of the channel, the average-bit-per-Joule performance decreases. Finally, it can be also seen that the CA incentive mechanism increases the average bit-per-Joule performance of the users.



(a)

(b)

Fig. 8: a) Average utility of a user as a function of increasing number of (N-1) users. w1 = w2 are set to be equal to 0.5; and b) Average utility of a user as a function of w_1.

In Fig. 7b, we evaluate the impact of mobility on the average bit-per-Joule performance of the proposed method, and also compare it with the method where global information is present. We consider the random walk model with mobility reflection to evaluate the impact of mobility [36]. The speed of a node is randomly selected from a uniform distribution between 0 meters/ second and a maximum speed of s_m meters/ second. It can be seen from the figure that as the moving speed of the devices increases, the average bit-per-Joule performance of the proposed method degrades. This is due to the reason that in a given iteration, when devices move then some of the devices may move out of the WiFi coverage of the devices that are serving them or receiving content from them. This in turn requires that some of these devices (which are no longer in the WiFi coverage of any content delivery devices) are given the content segments using the cellular interface. The Fig. 7b shows that the proposed method performs well for static to slow mobility scenarios. It is reasonable that a cooperative content delivery method using distributed WiFi devices may not be suitable for scenarios where devices are in high mobility scenarios such as in a car, as a distributed WiFi link has short coverage of around 40 to 60 meters, and for high moving users in a car there can be too many handovers which can lead to loss in cooperative content segment communication. However, on the other hand if users are in a high mobility scenario such as traveling on a high speed train then devices once again may obtain the benefits of the proposed method as devices in such scenarios are either static or in slow mobility relative to one another.

In Fig. 8a, we evaluate and compare the average utility obtained by a user i as a function of increasing number of $(N-1)$ users under different scenarios. It can be seen that the scenario in which the user i deviates (while all others follow), the average utility of user i is significantly less as compared to when it always follows the SB method with the FRDP mechanism. Moreover, it can be also seen that the average per user utility of other users who always follow the proposed method is greater than the user i which deviates. The Fig. 8a, also shows that the scenario where all N users always follow the proposed SB method with the FRDP mechanism performs better as compared to other methods.

In Fig. 8b, for different scenarios we present the average utility obtained by a user i as a function of the user's preference weight w_1, i.e., the user's preference weight for energy costs. The preference weight w_1 may depend on a particular device's battery condition. In Fig. 8b, it can be seen that when the user's preference weight w_1 for energy cost is small, then as compared to the other methods, the average utility obtained by the user i is significantly higher for the scenario in which all the users always follow the SB method with the FRDP incentive mechanism. It can be also seen that for higher preference weights such as $w_1 = 0.85$, and $w_2 = (1-w_1) = 0.15$, the proposed SB method with the FRDP mechanism performs the same as the other methods. We note that in practice, a user may prefer to have very high preference weight for energy costs when its battery energy is very low. In such scenarios it may not be efficient to select users with low batteries for CCD. In practice, there are softwares available that can report the battery condition of a device to the BS [37], and the BS using the proposed method can take this into account by simply not selecting those users that have low battery energy.

VIII. CONCLUSIONS

To address the problem of cellular network congestion in the context of content delivery to multiple users simultaneously, in this paper, we studied the use of multiple wireless interfaces for CCD. We showed that our proposed SB method which selects devices with high link quality for content delivery, leads to energy savings for devices and frequency carrier savings for a BS.

Mobile-to-mobile CCD requires users to contribute their resources, such as battery energy and device computation resources. Although a cellular BS assists in CCD, however, each mobile user is an independent entity who acts to maximize its own utility, and can deviate from the CCD method if a deviation could increase its utility. This motivated us to analyze the stability of the proposed SB method against selfish deviations using the framework of repeated games with an infinite time horizon. We showed that although the proposed SB method is efficient in terms of frequency carrier and energy savings performance, however, it is not an equilibrium against a selfish deviating user. To address this problem, we proposed a *carrier aggregation* based incentive mechanism called Follow-Reward and Disregard-Punish (FRDP) mechanism for the SB method. The proposed mechanism rewards the users that follow the BS selection by giving them CA incentives. It punishes the users that disregard the BS selection, by giving content to them only through a cellular interface using a single carrier. Our analytical and simulation results have shown that the SB method with the FRDP mechanism maximizes individual and network payoffs, and is stable against unilateral selfish deviations.

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