On the Selection of Best Devices for Cooperative Wireless Content Delivery

Bidushi Barua$^1$, Zaheer Khan$^1$, Zhu Han$^2$, Matti Latva-aho$^1$, Marcos Katz$^1$

1 Centre for Wireless Communications, University of Oulu, PO Box-4500, FI-90014, Finland.
2 University of Houston, USA.

{bbarua, zaheer.khan, matfa, marcos.katz}@ee.oulu.fi, zhan2@uh.edu

Abstract—Thanks to the smart device revolution, modern wireless devices have increased computational/storage capabilities and can also support for multiple network interfaces such as cellular and WiFi interfaces. Intelligent utilization of multiple network interfaces can address the problem of cellular traffic congestion and it can also increase the frequency resources of cellular networks. Cooperative content distribution (CCD) is one such technique that can be performed by using multiple wireless interfaces. In CCD, a device receives content from a base station on its cellular interface and distributes it to other devices in its vicinity through another wireless interface such as WiFi. However, due to the broadcast nature of the secondary links such as WiFi, even a single bad link can serve as a bottleneck in terms of the CCD performance. To address this problem, in this paper, we propose a device selection method for CCD that takes into account both the primary (cellular) and secondary link (WiFi/short-range) network interfaces. The proposed method incurs little overhead as it utilizes information such as acknowledgement of data packets, that already exists in the network. We evaluate and compare (with the other content delivery methods) the performance of the proposed method in terms of: 1) Number of carriers utilized by a cellular base station (BS); 2) Average bits-per-Joule performance; and 3) The average time required to deliver a content file. Moreover, we also take into account the impact of the presence of independent competing/interfering links (such as competing users in the unlicensed band) on the performance of the proposed method.

Index Terms—Cooperative content delivery, cellular networks, device to device communications, multiple network interfaces, and intelligent selection method.

I. INTRODUCTION

The increasing use of more powerful and capable smart devices has created dramatic increase in the usage of data demanding applications [1]. In cellular networks, to support data demanding applications the default operation today is that each user downloads the data content independently with its cellular connection. 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 applications.

Nowadays, wireless devices like smart phones and tablets are equipped with multiple network interfaces such as cellular, WiFi, Bluetooth and other short range technologies. A natural way to tackle the problem of traffic congestion is to take advantage of multiple network interfaces available on these devices by using these interfaces intelligently to cooperatively distribute data content among the users that are in proximity [1]. The practical use cases of cooperative distribution of the content to the users that are within proximity of one another include (but are not limited to): 1) Devices that access the same content at the same time. Examples of such content include videos (such as live sports game and popular YouTube content) being watched by a group of people on smart phones, tablets etc; 2) Devices that want to access popular content. Examples include popular audio and video content; and 3) Regular software updates on smart phones, tablets and laptops.

Design of cooperative techniques using multiple network interfaces for wireless content distribution to a group of users that are within proximity of each other is gaining increasing interest [2]-[3]. However, the problem of intelligent selection of devices for wireless content distribution while taking into account both the primary (cellular) and secondary link (WiFi/short-range) network interfaces has not been previously addressed. In much of the literature, the secondary links that are utilized for cooperative content delivery are considered to have the same quality in terms of transmit/receive performance [2]-[3]. However, in reality link qualities are different. Moreover, due to the broadcast nature of the secondary links, even a single bad link can serve as a bottleneck in terms of cooperative content delivery performance (such as in WiFi, where one bad link can severely reduce the total network performance).

The main contributions of this paper are:

- We propose a method called Select Best which performs intelligent selection of the devices (for wireless content delivery) that cooperatively distribute content to the other devices. While performing selection, it takes into account the quality of both primary (cellular) and secondary (WiFi, Bluetooth etc) links of users.
- Our proposed method incurs little overhead as it does not need to send acknowledgements of their received packets to the BS.
- We evaluate the performance of the proposed method in terms of: 1) Number of carriers utilized by the cellular base station (BS); 2) Average bits-per-Joule performance; and 3) The average time required to deliver a content file to all the users. We compare the proposed method against the methods in which: 1) Only primary (cellular) link interface is utilized to deliver content to all the users; and 2) The BS selects the devices for cooperative content.
distribution. However, the content distribution devices in this case are selected while taken into account only the cellular link interface of the devices.

- Finally, we also take into account the impact of the presence of independent competing/interfering links (such as competing users in the unlicensed band) on the performance of the proposed method.

The rest of this paper is organized as follows. Section II presents the related literature. The system setup is presented in Section III, while Section IV introduces the proposed method. In Section V we present, analyze and compare our proposed method to the related methods. Finally, Section VI summarizes our main conclusions.

II. RELATED WORK

Cooperative content distribution using multiple network interfaces has attracted the strong interest of wireless research community (see [4], [5], [6], [7] and references therein). The cooperative content distribution among devices in a cellular network can occur either in the licensed cellular frequency spectrum or in the secondary frequency spectrum such as in the unlicensed spectrum bands. In [5], a taxonomy of such methods is presented based on the spectrum used for cooperative communication (such as cooperative content distribution) among devices in a cellular network. The cooperative methods in [5] are mainly classified as the inband and outband cooperative communication methods. In the inband methods, licensed cellular spectrum is used by devices for cooperative communication. The main motivation behind such methods is that in licensed cellular spectrum a cellular operator has complete control over the spectrum [8], [9]. The inband methods can be further subdivided into underlay and overlay categories. In the underlay methods, both cellular and cooperative secondary links share the same radio frequency resources. This helps to improve the spectrum efficiency of cellular networks by reuse of spectral resources. However, it also requires the need for good interference management algorithms as both cellular and secondary links utilize the same frequency resources [10], [11], [12], [13], [14], [15]. In the overlay communication methods, secondary links are allocated to dedicated resources of the cellular spectrum. This eliminates the concerns of interference from secondary communications on cellular transmissions and vice versa. However, this reduces the amount of available frequency resources for cellular communications [16], [17], [18].

On the other hand, in the outband cooperative communication methods, the secondary links exploit the secondary spectrum resources such as the unlicensed bands. This eliminates both the interference issue between secondary and cellular links as well as the problem of reduction in available frequency resources for cellular communications due to the active secondary links. However, intelligent methods for cooperative content distribution are required as in the secondary spectrum (such as unlicensed bands) there can be other independent competing devices.

The authors of [19] propose the use of ISM band for secondary link communications in LTE. In [19], the secondary links are proposed to be grouped based on QoS requirement and only one link per group is allowed to contend for the WiFi channel. In [20], [21] Golrezaei proposes to cache popular videos on smart phones and exploit secondary links for their distribution among the interested users. Each cell is partitioned into clusters and non-overlapping contents are cached in the same cluster. When a user requests for a certain content, the BS checks the availability of that content in the cluster, the absence of which results in BS sending the content directly to the user; otherwise, the nodes within cluster are utilized for content distribution.

In this paper, we study the problem of intelligent selection of devices for wireless content distribution using multiple network interfaces. Unlike other works (discussed above), our research takes into account the link quality of the primary (cellular) and the secondary link (WiFi/short-range) network interfaces of the devices during the selection process. Moreover, our proposed method utilizes information already existing in the network, and hence incurs little overhead.

III. SYSTEM MODEL

A. Network model

Consider a cellular cell with a circular region of radius \( R \) as shown in Fig. 1. The BS is located at the center of the circle and there are \( N \) users in the cell who are interested in the same content. Let \( \mathcal{N} = \{1, 2, 3, \ldots, N\} \) represent the set of users that are interested in the same content. The location of each user \( i \), where \( (i \in \mathcal{N}) \), can be represented by the coordinates \((d_i, \theta_i)\), where \( d_i \) is the distance between the BS and the user, and \( 0 \leq \theta_i \leq 2\pi \). We consider two different distributions of \( N \) users within the cellular cell: 1) Users are randomly distributed around the BS (see Fig. 1a); and 2) Users are clustered, where we consider that there are \( n_c \) clusters in the cellular cell and each cluster has \( n_t \) users within it. Moreover, for comparison with the random deployment scenario it is ensured that \( n_c * n_t = N \) (see Fig. 1b).

B. Channel model

When only a cellular link is utilized for content delivery, a user independently downloads content using its own cellular
connection. For instance, if all $N$ users are served directly by the cellular BS then the BS needs to have $N$ independent parallel sessions or carriers. Consider the case where the cellular BS sends content to user $i$, for this case, we quantify the rate obtained as the Shannon capacity of the $i$th link. The instantaneous cellular rate at time $t$ of the $i$th link $R_{i,c}(t)$ can be expressed as

$$R_{i,c}(t) = W_c \log_2 \left( 1 + \frac{h_{BSi}(t)P_{i,c}}{W_cN_0} \right),$$

where $h_{BSi}(t)$ is the channel gain at the time $t$ between the BS and user $i$, and is given as $h_{BSi} = \frac{g_{ij}(t)}{(d_{BSi}^2)}$ with $\kappa$ being the path loss constant, $\alpha$ is the path loss exponent, $d_{BSi}$ is the distance between the BS and user $i$, and $\rho_f(t)$ is the fading gain at the time $t$. Any user $i$ has an average power constraint $P_{i,c}$. $W_cN_0$ is the noise power and $W_c$ is the cellular link bandwidth of a carrier utilized by the BS to deliver the content to user $i$.

When multiple network interfaces are utilized by the BS for cooperative content delivery (based on device selection method as explained in the next section). The selected devices using their WiFi link interface broadcast the same received data content to the remaining users within their vicinity. In practice, due to energy consumption reasons every node may do not want to broadcast the content to other nodes when selected as a candidate. In such scenarios some incentive mechanism needs to be designed. Design of such incentive mechanisms is our current ongoing research work. The success of receiving the data depends on the channel conditions between a selected broadcasting user and the receiving user. Every served node sends the number of packets received (successfully) from a candidate user (as mentioned in Step 5 of the proposed algorithm in Section IV), which is an indicator of the link quality of the candidates with the served nodes. We consider that each selected device has a coverage radius of $r_{SN}$, and if user $j$ is within the coverage of any selected device, the reception of data content can be successful; otherwise not. 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 selection methods for two different scenarios: 1) When there is no other independent active user or access point on the WiFi channel; 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 competing WiFi users are maximum loaded. In such scenarios, a selected device $i$ can still expect to get its ‘fair share’ $\frac{1}{N+1}$ 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 user $i$ (see [22] for details). Note that WiFi users are in general clustered as they are mostly active in areas with higher user density such as residential areas, universities and hospitals. To take this into account, we consider that there are $X$ circular regions or zones of active independent WiFi users, where $1 \leq X \leq 4$, and in each region there are $I$ competing WiFi users are active (see Fig. 2). The instantaneous rate at time $t$ of the $j$th link (that is not selected as the best device and utilizes WiFi interface for content reception) can be expressed as

$$R_{ij,W}(t) = \begin{cases} \frac{1}{A_c+1}W_w \log_2 \left( 1 + \frac{h_{ij}(t)P_{i,w}}{W_wN_0} \right), & \text{if } d_{ij} \leq r_{SN} \\ 0, & \text{otherwise,} \end{cases}$$

where $W_w$ is the bandwidth of the WiFi channel that is utilized by a selected device $i$, $P_{i,w}$ is the transmit power of selected device $i$, $h_{ij}(t) = \frac{g_{ij}(t)}{(d_{ij}^2)}$ with $\kappa$ being the path loss constant, $\alpha$ the path loss exponent, $d_{ij}$ the distance between the $i$th selected device and the receiving user $j$, $\rho_f(t)$ is the instantaneous fading gain, $W_wN_0$ is noise power and $N_c$ is the set of selected users.

C. Metrics for Evaluating/Comparing the Proposed Method

In this subsection, we present the considered metrics for evaluating/comparing the performance of the proposed method.

1) Cellular Carrier Utilized and Savings: Let consider that $N$ users are interested in a (similar) content file size of $S$ MBytes. Denote $N_{BS}$ the average number of carriers utilized by a cellular BS to deliver to the users this file using the select best method and $N_c$ the number of carriers utilized when the BS delivers directly to the users. Then average savings in the number of carriers per content file at the BS is given as

$$N_{sav} = N_c - \frac{\sum_{i=1}^{I_{MC}} N_{BS,i}}{I_{MC}}.$$  

Note that $I_{MC}$ is number of times the experiment is conducted.

2) Bits-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

$$E_C = \frac{1}{N} \sum_{i=1}^{N} \frac{R_{i,c}}{P_{i,c}}.$$  

where $R_{i,c}$ is the average rate of the $i$th user and $P_{i,c}$ the power utilized by the BS for that user. The average bit-per-joule performance of a user when the cellular BS delivers a
content file to the $N$ users using the select best method is given as

$$E_{BS} = \frac{1}{N_B} \left( \sum_{i=1}^{N_B} R_{i,c} P_{i,c} \right) + \frac{1}{N - N_B} \left( \sum_{i=1}^{N-N_B} R_{i,w} P_{i,w} \right)$$

(5)

where $R_{i,c}$ is the average rate of the $i$th user that is served by the BS directly, $P_{i,c}$ is the power utilized by the BS for that user, $R_{i,w}$ is the rate of the $i$th user that is served by the secondary link, $P_{i,w}$ is the power utilized by a secondary link for that user and $N_B$ is the number of selected best users.

3) Average Time to Download a File: The third metric that we consider is average time to download a content file of size $S$ MBytes. Average time to download for a user when the cellular BS delivers a content file directly to the $N$ users is given as

$$T_C = \frac{S}{N} \sum_{i=1}^{N} \frac{1}{R_{i,c}}.$$ 

(6)

Average time to download for a user when the cellular BS delivers a content file to the $N$ users using the select best method is given as

$$T_{BS} = \frac{S}{N_B} \sum_{i=1}^{N_B} \frac{1}{R_{i,c}} + \frac{S}{N - N_B} \left( \frac{S}{N_B} \sum_{i=1}^{N_B} \frac{1}{R_{i,c}} + \sum_{i=1}^{N-N_B} \frac{1}{R_{i,w}} \right)$$

(7)

IV. PROPOSED SELECT-BEST METHOD

In this section, we propose our Select Best (SB) method for intelligent selection of best wireless content delivery devices. The proposed method is described in Fig. 3 and the steps involving in the proposed method are further explained in detail as follows.

- 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. Note

![Fig. 3. Select best method for selection of best content delivery devices.](image)

![Fig. 4. Some example scenarios for coverage overlap between the selected users 1 and 2.](image)

(a) Scenario where user 1 and 2 are selected as candidate users and their coverage is non-overlapping.

(b) Scenario where user 1 and 2 are selected as candidate users and their coverage is slightly overlapping.

(c) Scenario where user 1 and 2 are selected as candidate users and their coverage is partially overlapping.

(d) Scenario where user 1 and 2 are selected as candidate users and their coverage is almost completely overlapping.
that the number \( N_r \) of candidate users that is 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 better to keep \( N_r \) small.

- Step 2: The short-range/WiFi link of the users are turned on by the BS.
- Step 3: The BS deliver content (packets) to the selected candidate users.
- Step 4: The candidate users broadcast the received content through WiFi links while other users listen.
- Step 5: The BS collects serving information, evaluates and stores the users served information 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 different candidate users. 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: 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 TUS 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, if a user receives the same packets from two different candidate users this can increase overhead in terms of energy and delay. To give further insight into the impact of users with overlapping coverage scenarios, we provide some examples in the subsequent subsection.

- Step 9: The BS selects the users with TVB > 0 as the potentially best \((N_{BP})\) 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 users is only serving another potentially best user, if yes, then it is removed from the list of best users as this potentially best user brings no additional value since it is serving another potentially best user that is already served by the cellular link directly. Otherwise, the potentially best user is selected as the best user. This process is repeated over all the potentially best users. Hence, in this way, a group of best users is selected to broadcast content. Finally, the BS checks if there is any user that is neither the best user nor the user served via one of the users. 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 best user selection process 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.

A. Example coverage overlapping scenarios

In this subsection, different examples of coverage overlapping among the candidate users are discussed and illustrated in Fig. 4. In Fig. 4a, both the candidates, users 1 and 2 have non-overlapping WiFi coverage, due to which it is beneficial to select both the users to distribute content to different users, and hence increase the coverage of cooperative content delivery (CCD). In Fig. 4b, candidates 1 and 2 have a WiFi coverage that is partially overlapping, where user 1 can serve A and B and user 2 can serve A, B and C. In such a case, it can be beneficial to select user 2 only for CCD, as user 1 brings no additional value in terms of user serving. In Fig. 4c, candidates 1 and 2 have a WiFi coverage that is partially overlapping, where user 1 is also in the coverage range of selected user 2.
Fig. 6. Average bit-per-Joule performance vs number of other competing users. a) The users are randomly deployed; and b) the users are deployed in clusters.

but not vice versa. However, both users 1 and 2 bring CCD benefit as user 2 can serve 1, B and C and user 1 can serve A and B, where A is not served by user 2. In Fig. 4d, users 1 and 2 have WiFi coverage that is completely overlapping. In this case, the user that has a better cellular link quality can be selected as the candidate user.

V. SIMULATION RESULTS

Using MATLAB we simulate a cellular cell of radius $R = 1$ 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 $r$ in the cellular cell (see Fig. 1b). 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 $k$ and $\alpha$ are set to 1 and 3, respectively. The transmitting and receiving 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 cellular rates between the BS and the users are considered to be in the range of 600 Kbps to 2 Mbps, and the WiFi transmission 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 users) 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 cellular BS delivers data to all users, whereas in methods 2 and 3 the content distribution process has two stages, i.e., where the cellular 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 users operating in the same WiFi channel on the performance of the proposed method, we consider that there are $X$ circular regions in the cellular cell and in each these regions $I$ independent users operate. The values of $I$ are varied between 0 to 50.

1) Number of carriers employed: In Figs. 5a and 5b, we plot the average number of 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).

It can be seen 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 also seen that when 50 active users are randomly distributed in the cell then the proposed method requires 7 carriers less than the method that utilizes cellular link only for content delivery. However, the real gains of the proposed method are evident in Fig. 5b when the same 50 users have clustered distribution (10 clusters with 5 nodes in each cluster). The proposed method for clustered distribution requires 43 carriers less than the method that utilizes cellular link only for content delivery.

2) Average bit-per-Joule performance: In Figs. 6a and 6b, for different scenarios, we present the average bit-per-Joule performance as a function of number of potential interferers (other independent competing) users in the cellular cell that utilize the same WiFi channel as the devices in the cooperative content communication. 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 show any change in performance and the cellular link-based selection method show little change in performance. On the other hand, although the performance of the proposed method degrades with increase in the number of other competing users. However, even for a large number of other competing users our proposed method outperforms the other two methods significantly. It can be also seen from the four figures that when the users in the cooperative content communication have the clustered distribution then their bit-per-Joule performance is strongly affected (with the increasing number of other competing users) as compared to when the users are randomly distributed.

3) Average time to download a content: The average time a user takes to download a content file of 500Mbits is shown in Fig. 7 as a function of number of potential interferers I. It is seen that the proposed method takes the least time in average to download a content as compared to time taken with the conventional cellular method and the cellular link-based selection method when no other competing users are present on the WiFi channel. In presence of other competing users, the conventional cellular method is unaffected as can be intuitively expected. On the other hand, the performance of the proposed method becomes worse than the conventional cellular method when a large number of competing users are present, though it is significantly better than the cellular link-based selection method, even for large number of competitors.

VI. CONCLUSION

To address the problem of cellular network congestion, we studied the intelligent selection of the content delivery devices to deliver content to more devices for the scenarios where several wireless users are interested in the same content or are interested in the same popular content, and they are in proximity of one another. Considering that user devices are often equipped with more than one network interfaces, we presented a method for the selection of the content delivery devices which takes into account both the primary (cellular) and the secondary network interface of a device. Our results showed that intelligent use of multiple network interfaces allow savings (at a cellular base station) in terms of number of carriers utilized by it and the average bits-per-Joule performance of a user is also increased in the cellular network.

REFERENCES


