DELAY-AWARE WI-FI OFFLOADING AND NETWORK SELECTION

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ABSTRACT:

To accommodate the explosive growth in mobile data traffic, both mobile cellular operators and mobile users are increasingly interested in offloading the traffic from cellular networks to Wi-Fi networks. However, previously proposed offloading schemes mainly focus on reducing the cellular data usage, without paying too much attention on the quality of service (QoS) requirements of the applications. In this paper, we study the Wi-Fi offloading problem with delay-tolerant applications under usage based pricing. We aim to achieve a good tradeoff between the user's payment and its QoS characterized by the file transfer deadline. We first propose a general Delay-Aware Wi-Fi Offloading and Network Selection (DAWN) algorithm for a general single-user decision scenario. We then analytically establish the sufficient conditions, under which the optimal policy exhibits a threshold structure in terms of both the time and file size. As a result, we propose a monotone DAWN algorithm that approximately solves the general offloading problem, and has a much lower computational complexity comparing to the optimal algorithm. Simulation results show that both the general and monotone DAWN schemes achieve a high probability of completing file transfer under a stringent deadline, and require the lowest payment under a no stringent deadline as compared with three heuristic schemes.

Index Terms: *DAWN, Mobile data offloading, cellular and Wi-Fi integration, dynamic programming, threshold policy.*

I. INTRODUCTION

Mobile cellular networks nowadays are often heavily loaded due to the huge amount of mobile data traffic generated, for example, through mobile web browsing and mobile video applications. According to Cisco's forecast, mobile data traffic will increase by 11-fold between 2013 and 2018 globally. On the other hand, the mobile cellular network capacity is growing at a much slower pace, so that it is likely that the mobile traffic demand will exceed the network capacity in the short to medium term. As a result, there is an urgent need from the mobile operators (MOs) worldwide to increase the network capacity in a cost-effective and timely manner. An efficient way to ease the cellular congestion is to use complementary technologies, such as Wi-Fi, to offload the traffic originally targeted towards the cellular network.

There are two main approaches for the initiation of Wi-Fi offloading, namely user-initiated and operator-initiated offloading. In the *user-initiated* offloading, the mobile user (MU) is responsible for selecting the network technologies that it intends to use. In the *operator-initiated* offloading, however, the operator profile stored in the mobile device prompts the connection manager to initiate the offloading procedure. The MOs would prefer the operator-initiated offloading, as it gives them a better control on users' network selections. However, since the operator-initiated offloading involves complicated network control between the MOs and the MUs, further standardization and development are still under way. Currently, the user initiated offloading is the more popular choice due to its simplicity in implementation, and it will be the focus of this paper. New functionalities in some recently proposed IEEE and 3GPP architectures can provide MUs with useful network information for the user-initiated offloading. In Hotspot 2.0, which is based on the IEEE 802.11u standard, the network discovery and selection functionality advertises the network information related to the access network type, roaming consortium, and venue information through management frames.

The access network discovery and selection function (ANDSF) server, proposed in 3GPP Release 11, can assist an MU to choose a suitable Wi-Fi network by providing it with a list of preferred access networks and the access network discovery information. Moreover, it is envisaged that network information, such as real-time load and radio conditions, can be broadcast to the MUs through the system information block

(SIB) messages currently used in the LTE system [10, pp. 46]. With these new architectures for cellular and Wi-Fi integration, MUs can make intelligent network selection and offloading decision based on real-time network load and price information. In addition, the standardization effort from the industry has been accompanied by a series of efforts on the characterization of *Wi-Fi offloading* performance from the academia. Recently, measurement studies demonstrated that Wi-Fi offloading can significant reduces the cellular network congestion. In fact, the potential benefit of data offloading is even more significant for *delay-tolerant* applications, such as email, movie download, and software update, which can tolerate delays ranging from several minutes to several hours without significant negative impact on users' satisfactions. For example, the survey reported that more than half of the respondents are willing to wait for 10 minutes to stream YouTube videos and 3–5 hours to download a file when a monetary incentive is given. In this paper, we study the user-initiated Wi-Fi offloading problem for delay-tolerant applications, where a user aims to minimize its total data usage payment under *usage-based pricing*, while taking into account the deadline of its application. Previous works on user-initiated Wi-Fi offloading policy, which includes, mainly focus on reducing the cellular data usage without paying too much attention to the quality of service (QoS) of the user's application.

As an example, consider the on-the-spot offloading (OTSO) scheme that most smart phones are using by default [14]. The OTSO scheme adopts a simple offloading policy that an MU offloads its data traffic to a Wi-Fi network whenever possible. However, our simulation study suggests that it is not always desirable to offload to Wi-Fi whenever possible, especially when the Wi-Fi network is highly loaded and the deadline is tight. However, in general, it is challenging to achieve a good balance between the total payment and the QoS when taking various factors such as network conditions and delay deadlines into consideration.

First, we consider a general user offloading scenario, and formulate the delay-aware Wi-Fi offloading problem as a finite-horizon sequential decision problem.

We propose a general Delay-Aware Wi-Fi Offloading and Network Selection (DAWN) algorithm, which achieves a good tradeoff between the total payment and the QoS. However, in general, a sequential decision problem is computationally intractable unless the optimal policy has a threshold structure. To this end, based on the concepts of super additively and subadditivity, we derive sufficient conditions under which the optimal policy exhibits threshold structures in terms of both the time and the remaining file size to transfer. It motivates us to design the monotone DAWN algorithm with a much lower computational complexity that approximately solves the general offloading problem. To the best of our knowledge, this is the first paper that studies offloading algorithm design analytically, which tradeoffs a user's payment and QoS.

The insights obtained, even under the single-user setting in the user initiated offloading, are crucial for us to understand the more complicated multi-user offloading problems in commercial networks. In summary, the main contributions of our work are as follows:

- Optimal user-initiated offloading algorithm: We consider the Wi-Fi offloading problem for delay-tolerant applications, and propose a general DAWN algorithm that achieves a good tradeoff between total data usage payment and the user's QoS.
- Low-complexity approximation offloading algorithm: We derive sufficient conditions under which the optimal policy has a threshold structure, and propose a monotone approximation DAWN algorithm with a much lower computational complexity.
- Optimal offloading decisions: Simulation results show that the general and monotone DAWN algorithms achieve a high probability of file transfer completion and require a low

payment as compared with three heuristic schemes.

- We also show that Wi-Fi offloading may not be desirable under a tight deadline constraint and a congested Wi-Fi network.

II. EXISTING SYSTEM

Congestion-Aware Network Selection and Data Offloading

Wi-Fi offloading is a financially savvy way to deal with give prompt limit alleviation to the congested territories in a cell system. Notwithstanding, beforehand proposed plots fundamentally concentrate on reducing the cell clog by offloading the information movement to Wi-Fi however much as could be expected, yet without orderly contemplations of the system blockage, exchanging punishment, and valuing in the systems. In this paper, we consider the system determination and information offloading issue in a coordinated cell Wi-Fi framework by consolidating the down to earth contemplations of

i) user versatility,
ii) location, client, and time subordinate Wi-Fi availabilities,
iii) network subordinate exchanging time and exchanging cost for changing system associations, and
iv) Usage based evaluating into our demonstrating. We detail the collaborations of the clients' blockage mindful system choice choices over different time openings as a non-helpful system choice amusement (NSG), where the procedure of every client compares to a course on a diagram.

- We demonstrate that the NSG is proportional to a clog amusement, which infers that the diversion has the limited change property. Therefore, when the players over and again perform better reaction upgrades, the framework is ensured to meet to an unadulterated Nash harmony. Reenactment results demonstrate that our proposed NSG plan accomplishes a superior burden adjusting than two static heuristic plans.

III SYSTEM MODEL

As shown in Fig. 1, we consider an integrated cellular Wi-Fi system, where the Wi-Fi networks are tightly integrated with the cellular network in terms of the radio frequency coordination and network management [8]. The networks are indexed by $n \in N = \{1 . . . N\}$, where n = 1 denotes the cellular network, and $n \in N_{wifi} = \{2 . . . N\}$ denotes a Wi-Fi network. We consider a slotted system indexed by time slot $t \in T = \{1, . . . ,T\}$ of length Δ_t. Let be the capacity of Network n _ N, and let $x^{(n,t)}$ be the background traffic of network $n \in N$ at time $t \in T$. The background cellular traffic load $x^{(1,t)}$ can be generated from users who can only gain access to the cellular network, but not the Wi-Fi network (e.g., MUs who do not move into the Wi-Fi coverage areas, or MUs with devices not supporting Wi-Fi). The background Wi-Fi traffic load $x^{(n,t)}$ of network $n \in N_{wifi}$ can be generated by users who can only access the Wi-Fi network $n \in N_{wifi}$, but not the cellular network (e.g., desktop computers).

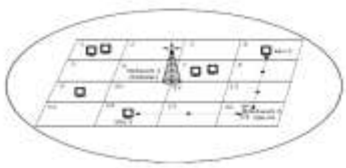
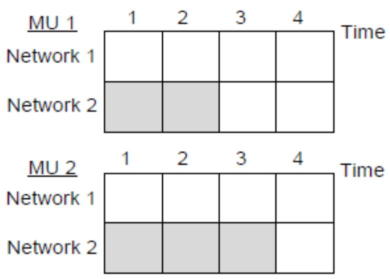


Fig. 1. An example of the network setting

Where N = {1, 2} is the set of networks. We assume that the cellular network (i.e., network 1) is available at all the locations, while the Wi-Fi network (i.e., network 2) is location, time, and user dependent. The MUs are moving within a set of locations L = {1 . . . 16} over multiple time slots.



Due to the difference in the mobility patterns and Wi-Fi availabilities of the MUs, their network availabilities at different time are different in general. In Fig. 2, we show an example of the heterogeneous network availabilities of MU 1 and MU 2 shown in Fig. 1.

In this work, we define the *utility* of an MU at a particular time as its received throughput. Let m be the number of MUs who have chosen network $n \in N$ at time $t \in T$. The network throughput at that time is equal to $\frac{u^{(n)}}{m+x^{(n,t)}}$ which is inversely proportional to the congestion level in the network [17]. We suppose that the MO adopts the commonly used *usage-based pricing*, where the required payment of an MU is directly proportional to its data usage.

III.1 THRESHOLD POLICY AND MONOTONE DAWN ALGORITHM

In this section, we establish sufficient conditions under which the optimal policy has a *threshold* structure in the remaining file size *k* and time *t*. We then propose a monotone DAWN algorithm accordingly, which approximately solves problem (7) in the general case with a lower computational complexity. Thus, the results cannot be obtained by a direct application of the standard DP theory. Specifically, we make the following assumptions for deriving the optimal policy in this section:

Assumption 1: (a) The penalty function $h(k)$ is convex and non-decreasing in k; (b) Wi-Fi is free to the MU (i.e., $p(l, 2) = 0$, $\forall l \in L(1)$); (c) The cellular price is location-independent (i.e., $p(l, 1) = p(l,1)$, $\forall l \in L$, $l = l$); (d) The cellular and Wi-Fi data rates are location- independent (but these two rates are different in general). That is, $\mu 1 = \mu(l, 1)$, $\forall l \in L$ and $\mu 2=\mu(l, 2)$, $\forall l \in L(1)$; and (e)We approximate $\min\{k, \mu(l, 1)\}$ in (3) by $\mu(l, 1)$ for action $a = 1$.

Notice that

(a) a convex penalty function can be used to model the increasing marginal penalty for every additional unit of file segment not yet transferred. It is similar to the idea that a concave utility function can be used to model the diminishing marginal utility.

(b) Free Wi-Fi can often be found in places such as homes, offices, or coffee shops.

(c) Location-independent cellular price is widely used in practice.

(d) is a good approximation when the cellular and Wi-Fi data rates across different locations have a small variance.

(e) is a technical approximation for simplifying the structure of the optimal policy. With Assumption 1, the cost at state ***s*** with action *a* at time slot *t* is modified from (3) as

$$c_t(s,a) = c_t(k,l,a) = I(a=1)q = \begin{cases} q, & if\ a=1 \\ 0, & otherwise, \end{cases}$$

where $a \in A(l)$, $I(\cdot)$ is the indicator function, and $q = \mu(l, 1)p(l, 1)$. As a result, $\psi t(k, l, a)$ in (9) can be rewritten as

$$\psi_t(k,l,a) = I(a=1)q + \sum_{l' \in \mathcal{L}} p(l'|l) v_{t+1}([k-\mu(l,a)]^+, l')$$

A. Properties of the Optimal Policy

First, we discuss some analytical results related to the properties of the optimal policy under Assumption 1.

Lemma 1: (a) $vt(k, l)$ is a non-decreasing function in k, $\forall l \in L$, $t \in T$. (b) $vt(k, l)$ is a non-decreasing function in t, $\forall k \in K$, $l \in L$.

The proof of Lemma 1 is given in [23]. Intuitively, given a fixed location $l \in L$, the expected cost is higher when k is larger (i.e., the remaining file size to transfer is larger) or when t is larger (i.e., it is closer to the deadline). Next, we characterize the optimal transmission policy at a location $l \in L(1)$ with Wi-Fi. Since Wi-Fi is free for use, Lemma 2(a) states that action $a = 2$(i.e., using Wi-Fi) is always preferred to action $a = 0$ (i.e., remaining idle). Lemma 2(b) states that if the Wi-Fi data rate is higher than the cellular data rate, then the MU should always use Wi-Fi.

Lemma 2: For any location $l \in L(1)$ (where Wi-Fi is available), we have:

(a) $\psi_t(k,l,a) \geq \psi_t(k,l,2), \forall k \in K, t \in T$.

(b) $If\ \mu(l,1) \leq \mu(l,2), then\ \delta_t^*(k,l) = 2, \forall k \in K, t \in T$

B. Threshold Structure of the Optimal Policy

To show the threshold policy in dimension k, we need to leverage on the concepts of super additively and subadditivity [17, pp. 103]. Specifically, with the assumptions we made on the penalty function and data rates, we show in [23] that ψt (k, l, a) is superadditive or subadditive on K × A˜(l) under different conditions. Then, with δ∗ t (k, l) defined in (12), we can establish the threshold structure of the optimal policy in dimension k [17, pp. 104, 115]. Definition 1: Given l ∈ L, the function ψt(k, l, a) is super additive on K × A˜(l) if for ∀ kˆ, kˇ ∈ K and ∀aˆ, aˇ ∈ A, where ˆk ≥ ˇk and ˆa ≥ ˇa, we have

$$\psi_t(\hat{k},l,\hat{a}) + \psi_t(\check{k},l,\check{a}) \geq \psi_t(\hat{k},l,\check{a}) + \psi_t(\check{k},l,\hat{a}).$$

The function *ψt* (*k, l, a*) is *subadditive* on *K* × *A˜*(*l*) if the reverse inequality always holds.

To prove the threshold policy in dimension *t*, we show in [24] that the incremental changes of *vt* (*k, l*) with respect to *k* is non-decreasing in time *t*.

C. Monotone DAWN Algorithm

With the threshold structure in both dimensions *k* and *t* from Theorems 2 and 3, we propose Algorithm 2 with a much lower computational complexity than Algorithm 1. In Algorithm 2, it should be noted that we choose to characterize the optimal policy *π∗* using the thresholds (*k∗*(*l, t*)*, ∀ l ∈ L, t ∈ T*) in the file size dimension in (18) and (20). In the planning phase of Algorithm 2, we use the procedure THRESHOLD to obtain the set of thresholds (*k∗*(*l, t*)*, ∀ l ∈ L, t ∈ T*) (line 10) in dimension *k*. Since we execute the algorithm backward from *t* = *T* to *t* = 1, after we have found the threshold *k∗*(*l, t*) at time *t*, we can reduce the search space of *k∗*(*l, t* − 1) at time *t* − 1 by Theorem 3(a).

By knowing the threshold structure in both dimensions *k* and *t* in Theorems 2 and 3, we can speed up the computation of the optimal policy. Let *A*th *⊆ A˜*(*l*) be the set of feasible actions that we should consider (procedure line 8) for the optimal policy. Instead of considering the two possible actions in *A˜*(*l*) = *{*1, 2*}* for *l ∈ L*(1) and *A˜*(*l*) = *{*0, 1*}* for *l ∈ L*(0) in (15) for (16), we can reduce the amount of computation by only considering one possible action in *A*th under two conditions:

(i) When *k* < *k∗*(*l, t* + 1), we know from Theorem 3(a) that *k* < *k∗*(*l, t*), so we only need to consider *A*th = *{j}* with one element (procedure line 2).

(ii) (ii) When we have reached the threshold that*k* > *k∗* (*l, t*), we know from Theorem 2 that we only need to consider *A*th = *{*1*}* with one element (procedure line 11).

In both cases (i) and (ii), *A*th becomes a singleton, and the minimization in line 8 of the procedure is readily known. As a result, the computational complexity is reduced from *O*(*KLT/σ*) in Algorithm 1 to approximately *O*(*L*max*{K/σ, T}*) in Algorithm 2 [16]. In the second phase, we determine action *a* based on the threshold optimal policy in dimension *k* stated in Theorem 2. Specifically, the decisions in lines 16, 19, and 21 are due to (18), (20), and (22), respectively.

Algorithm 2 *Monotone DAWN Algorithm.*

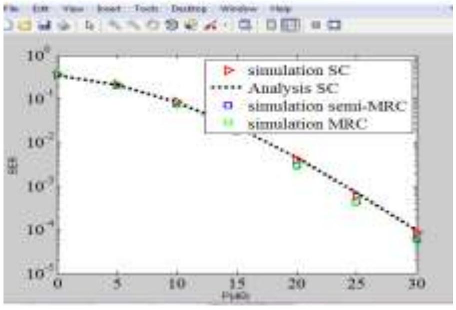
Planning Phase (for $\mu_2 \le \mu_1$):
Set $v_{T+1}(k, l), \forall k \in \mathcal{K}, l \in \mathcal{L}$ using (11)
Set $t := T$
while $t \ge 1$
    for $l \in \mathcal{L}$
        Call THRESHOLD procedure
    end for
    Set $t := t - 1$
end while
Output the thresholds $(k^*(l, t), \forall l \in \mathcal{L}, t \in \mathcal{T})$ for the transmission and Wi-Fi offloading phase
Transmission and Wi-Fi Offloading Phase:
Set $t := 1$ and $k := K$
while $t \le T$ **and** $k > 0$
    Determine the location index l from GPS
    If $l \in \mathcal{L}^{(0)}$
        If $k \ge k^*(l, t)$, Set $a := 1$, **else**, Set $a := 0$, **end if**
    else if $l \in \mathcal{L}^{(1)}$
        If $\mu_2 \le \mu_1$
            If $k \ge k^*(l, t)$, Set $a := 1$,
        else,
            Set $a := 2$,
        end if
    end if
    If $a > 0$
        Send $\mu(l, 1)$ bits to the cellular network if $a = 1$ or offload $\mu(l, 2)$ bits to the Wi-Fi network if $a = 2$
        Set $k := [k - \mu(l, a)]^+$
    end if
    Set $t := t + 1$
end while

procedure THRESHOLD
If $l \in \mathcal{L}^{(0)}$, Set $j := 0$, **else**, Set $j := 2$, **end if**
Set $\mathcal{A}^{\text{th}} := \{j\}$, $k := 0$, and $flag := 0$
while $k \le K$
    if $k \ge k^*(l, t + 1)$ and $flag = 0$
        Set $\mathcal{A}^{\text{th}} := \{j, 1\}$ and $flag := 1$
    end if
    Calculate $\psi_t(k, l, a), \forall a \in \mathcal{A}^{\text{th}}$ using (14)
    Set $\delta_t^*(k, l) := \arg\min_{a \in \mathcal{A}^{\text{th}}} \{\psi_t(k, l, a)\}$
    Set $v_t(k, l) := \psi_t(k, l, \delta_t^*(k, l))$
    if $\delta_t^*(k, l) = 1$ and $flag = 1$
        Set $\mathcal{A}^{\text{th}} := \{1\}$, $k^*(l, t) := k$, and $flag := 2$
    end if
    Set $k := k + \sigma$
end while

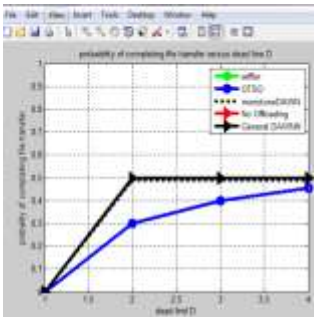
IV. EXPERIMENTAL RESULTS

In this section, we evaluate the performance of the general and monotone DAWN schemes by comparing them with three benchmark schemes in terms of the total cost, probability of completing file transfer, and the total payment. We also illustrate the threshold policy stated in Theorem. For each set of system parameter choices, we run the simulations 1000 times with randomized Wi-Fi locations, data rates in the cellular and Wi-Fi networks, and the user mobility trajectories, and show the average value. The MU is moving within $L = 16$ possible locations in a four by four grid.

To generate the trajectory of the MU, we consider the state transition probabilities, where we assume the probability that the MU stays at a location between two consecutive time slots. Moreover, it is equally likely for the MU to move to any one of the neighbouring locations.Notice that it is very different from the policy in the special case as stated in Theorem 2, where the MU would not stay idle even when there is no chance to complete the file transfer. To sum up, the penalty function has a significant impact on the optimal policy, and it should be chosen carefully according to the QoS requirement of the application.



(a)



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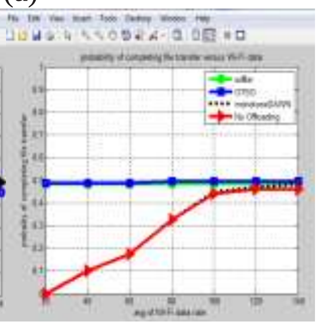
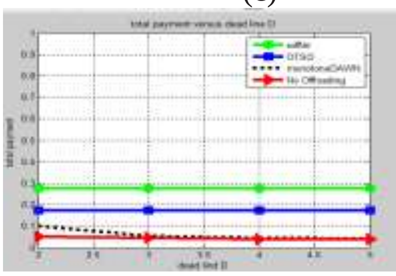
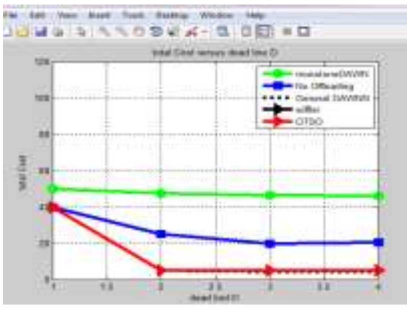


(c)



(d)



(e)

Figure: As show (a): Performance between BER and Probability compare different Simulation results (b) Probability of Completing file transfer versus dead line D (c) probability of completing file transfer versus Wi-Fi data(d) total payment versus dead line D (e) total Cost versus dead line D

V. CONCLUSION

In this paper, we studied the user-initiated Wi-Fi offloading problem for delay-tolerant applications under usage-based pricing. The user aims to minimize its total data usage payment, while taking into account the deadline of the file transfer. We first proposed a general DAWN algorithm for the general case using dynamic programming. We then established sufficient conditions under which the optimal policy has a threshold structure in both dimensions *k* and *t*. As a result, we proposed a monotone DAWN algorithm with a lower complexity that approximately solves the general offloading problem. It should be noted that the proposed algorithms are highly non-trivial, and they cannot be obtained simply by a standard application of dynamic programming. Contrary to the practices in some heuristic schemes that favour offloading traffic to Wi-Fi networks whenever possible, our simulation results showed that it is not always optimal for a user to perform Wi-Fi offloading when the deadline requirement is stringent and the data rate in the cellular network is much higher than that in the Wi-Fi network (e.g. a 4G LTE-A cellular system versus a congested Wi-Fi network). On the other hand, when the file transfer can be completed easily by the deadline, the delay-aware design in DAWN and Wiffler helps reduce the payment of the users.

Overall, our results suggested that future cellular and Wi-Fi integration system should include dynamic offloading policies that take into account the users' QoS and the real-time network loads, instead of using simplistic and static offloading policies. In this work, we have focused on the single file transfer by a given deadline. For future work, we will consider the case of multiple file transfers at the same time, and solve the problem by dynamic programming with additional states and decision variables.

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