Data Offloading in Mobile Cloud Computing Based on Markov Decision Process

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***Abstract*—Cellular network is facing severe traffic overload problem caused by phenomenal growth of mobile data. Offloading part of the mobile data traffic from cellular network to alternative networks is a promising solution. In this paper, we study mobile data offloading problem under the architecture of mobile cloud computing (MCC), where mobile data can be delivered by cellular, WiFi and device-to-device (D2D) networks. In order to minimize the overall cost for data delivery task, it is crucial to reduce cellular network usage while satisfying delay requirements. In our proposed model, a portion of the cellular data traffic is offloaded through WiFi and/or D2D networks. We formulate the data offloading task as a finite horizon Markov Decision Process (FHMDP). We first propose a hybrid offloading algorithm for mobile data with different delay requirements. Moreover, we establish the sufficient conditions for the existence of threshold policy. Then, we propose a monotone offloading algorithm based on threshold policy in order to reduce the computation complexity. The simulation results show that the proposed offloading approach can achieve minimal communication cost compared with other three offloading schemes.**

***Index Terms*—Mobile data offloading, device-to-device communication, mobile cloud computing, Markov decision process.**

I. Introduction

With the increase of the number of smart mobile devices and data heavy mobile applications, such as video streaming and cloud backup, global mobile traffic has been growing dramatically in recent years. According to a report from Cisco, global mobile data traffic grew 74% in 2015, while mobile network (cellular) connection speeds only grew 20% [1]. The growing speed of mobile traffic will push the current cellular network to the limit. The Quality of Experience (QoE) of mobile services will not be guaranteed without the high-speed and stable network connections between mobile service subscribers (MSs) and mobile network operator (MNO). However, it is impractical to keep extending the current cellular network infrastructure to improve QoE, given the corresponding expensive investment. In order to cope with this problem, mobile data offloading technology can be an alternative solution. Offloading is considered as a promising technique to move data traffic from cellular network to other wireless networks; indeed, it represents a complementary wireless technology to transmit data originally targeted to flow through cellular network [2]. When MNO sends mobile data to MS, it will be able to choose from many wireless networks instead of only cellular network. In addition to cellular network, current target wireless networks include WiFi, femtocell and D2D networks.

WiFi offloading is considered as a promising solution to reduce mobile data traffic in cellular network. WiFi Access Points (APs), covered by cellular network, can be used efficiently to reduce data traffic [3, 4]. The authors in [5] show that about 65% of data traffic in cellular network can be offloaded to WiFi network. The result is based on the assumption that most of the time, MS stays at home/office. However, when MS moves around in cellular network, the WiFi connection time is reduced greatly. The temporal coverage decreases to 11%, when MSs move around [6]. Although WiFi APs can provide better data rate than cellular network, their coverage area is much smaller than cellular network [7, 8].

Another mobile offloading method, called opportunistic offloading, is based on D2D networks [9], where mobile devices can connect with each other directly. The data transmission uses the strategy called store-carry-forward. In this strategy, some mobile users can store data in the buffer (called mobile helpers, MHs), carry the data when they are moving, and forward the data to other mobile users (called mobile subscribers, MSs) when they can connect with each other [10, 11]. This strategy requires a long delay and is widely used in D2D network. When MNO wants to deliver data to a set of MSs, it can first send the data to some MHs. Then, MHs will help transmit data to MSs using opportunistic connections. With more than half a billion mobile devices and connections added in 2015 [1], D2D network is becoming an important data delivery scheme. Unlike WiFi APs, MHs, which carry mobile data, can move randomly. However, the data rate of D2D network is low and the mobility patterns of MHs or MSs are difficult to predict.

In this paper, we consider a hybrid offloading model for a single MS in MCC, where MS can receive mobile data from cellular, WiFi and D2D networks. In MCC, both cellular and WiFi networks receive mobile data from cloud and then transmit the data to mobile users [12, 13]. In this model, MS moves around in the coverage area of cellular network. Since the coverage area of cellular network can be large, there will be many WiFi APs under the coverage range. We assume that both the base station and WiFi APs are located at some fixed sites; mobile users (including MSs and MHs) can receive data directly from WiFi or cellular networks. MHs can also transmit data to other MSs. In the hybrid offloading model, MNO can deliver mobile data to MSs with three methods in MCC: (1) WiFi AP based mobile data delivery: MNO can send data directly to the mobile user if the user location is covered by WiFi. Since the data rate and stability can be guaranteed, this will be the best situation MNO can expect; (2) MH based mobile data delivery: It is based on MHs willing to share their mobile device resources to help MNO with data delivery process. MHs get rewards from MNO in return; the coverage area of MHs can be quite small. The success of this delivery method is based on two factors: (a) MHs and MSs request the same kinds of data, and (b) they are near to each other; and (3) cellular network based mobile data delivery: When a mobile user cannot receive the desired data using the first two methods, MNO will send data to MSs using this method.

A preliminary version of this work will be published in [14]. In this paper, we extend the previous work with the analysis of optimal policy structure and new monotone offloading algorithm. The main contributions of our paper can be summarized as follows:

- We propose a hybrid offloading model, where mobile data can be delivered through three wireless networks, namely cellular, WiFi and D2D networks. MNO can decide when to use which network to transmit data in order to minimize the total communication cost.
- We formulate the data offloading problem in hybrid wireless networks as a Finite Horizon Markov Decision Process (FHMDP), and propose an offloading algorithm that can support different delay requirements (i.e., loose and tight delay tolerant).
- We prove that there exit threshold structures in the optimal policy. Then, we propose a monotone offloading algorithm for generating threshold policy with lower computation complexity.
- The simulation results show that our algorithm achieves the best cost, compared to three offloading schemes.

The rest of this paper is organized as follows. Section II reviews the related work. Section III describes the hybrid mobile data offloading model. Section IV formulates the FHMDP model. Section V proposes an hybrid offloading algorithm based on value iteration. Section VI establishes the sufficient conditions for the existence of threshold policy and proposes a monotone offloading algorithm based on threshold policy. Section VII evaluates the performance of the proposed offloading scheme. Finally, Section VIII concludes the paper.

II. Related work

MCC can support mobile devices access cellular, WiFi and D2D networks [15]. Most existing contributions [16, 17] focus on mobile computation offloading problem, which means migrating resource-intensive computations from MS to cloud. In this paper, we consider how to implement mobile data delivery in MCC by employing offloading technology. In the following, we present a survey of prior work aiming to offload cellular traffic to other mobile networks, including WiFi and D2D networks.

Several contributions have shown the benefits of offloading mobile data from cellular network to WiFi network. Song *et al.* [18] investigated offloading schemes for cellular and WLAN integrated networks. They considered the WLAN-first resource allocation scheme where WLAN connection is used whenever possible, in order to benefit from low cost and large bandwidth of WLAN. Siris *et al.* [19] investigated the methods for enhancing mobile data offloading from mobile networks to WiFi APs by using mobility prediction and prefetching techniques. They evaluated these methods in terms of offloading ratio, data transmission time and cache size when using prefetching. Cheng *et al.* [20] presented an analytical framework for offloading cellular traffic to WiFi network using queuing theory. They evaluated the offloading performance in terms of average service delay. Mehmeti *et al.* [21] evaluated the performance of on-the-spot mobile data offloading. They analyzed the performance improvement by WiFi-based offloading using queuing theory. Jung *et al.* [22] proposed a network-assisted user-centric WiFi-offloading model in a heterogeneous network; the objective was to maximize throughput for each MS by utilizing network information.

Other contributions have shown the possibility of offloading mobile data from cellular network to D2D network. The main idea is to transmit mobile data using opportunistic communications among MSs; this has been shown to provide significant wireless capacity gains. Vinicius *et al.* [23] proposed a multi-criteria decision-making framework for data offloading from 3G network to D2D network. The framework avoids changes in the infrastructure by employing only user knowledge to select MHs. It shows that delay tolerant applications can offload six-fold mobile data compared to delay sensitive applications. Sciancalepore *et al.* [24] considered data offloading in D2D network with heterogeneous node mobility patterns. They used an optimization method to minimize cellular network traffic while satisfying the applications' constraints. Filippo *et al.* [25] proposed a method, called DROiD, to control popular data distribution in D2D network; the aim was to minimize the usage of infrastructure resources. They did show that the proposed method can offload a significant amount of data from cellular network to D2D network under tight delivery delay constraints. Andreev *et al.* [26] investigated the offloading method from cellular network to D2D network. They demonstrated that assisted offloading of cellular user sessions into D2D links improves the degree of spatial reuse and reduces the impact of interference.

Since the coverage area of D2D network is flexible with the movement of MHs, it can help offload data when WiFi connections are not available, especially for transmitting small size data, due to the short connection time and low data rate. However, since the data rate of WiFi network is higher than that of D2D network and WiFi network is more stable than D2D network, WiFi based offloading generally outperforms

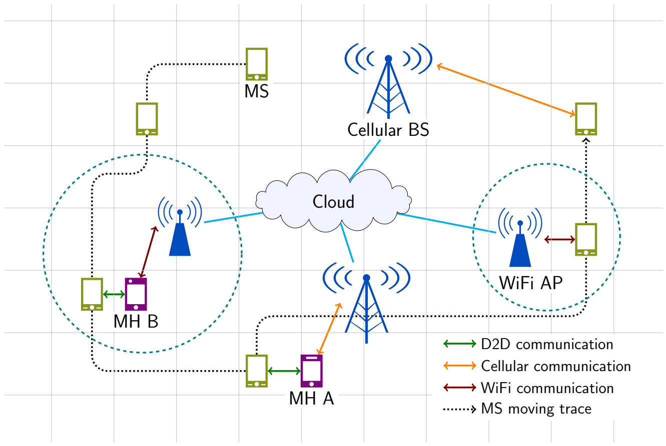


Fig. 1: Data offloading in Mobile Cloud Computing

D2D based offloading from MS's perspective [8]. Notice that D2D based offloading can offload significant mobile data from MNO's perspective, since the number of MHs can be quite large. In the simple case, WiFi APs can be considered as a special kind of MHs. Compared with MHs, WiFi APs are installed at some fixed locations and have more bandwidth.

We conclude that most existing contributions are based on WiFi offloading or opportunistic networks, without considering the combination of different mobile networks. In this paper, we consider a hybrid offloading model, where mobile data can be offloaded to WiFi and D2D networks, and MS can receive data from cellular, WiFi and D2D networks. Our objective is to minimize the overall cost for data delivery for MS while satisfying delay requirements for different data types.

III. System Model

In this section, we present our system model to enhance data offloading in mobile cloud. In our model, we consider that mobile devices can access cloud services through multiple wireless networks, as shown in Fig. 1: (1) WiFi network. WiFi APs provide opportunistic WiFi communication (e.g., WLAN) for MS within its working coverage, and connect to distant cloud infrastructure through wired network; (2) Cellular network. Cellular base stations (BSs) provide seamless cellular communication (e.g., 4G) for MS, and connect to cloud through wired network; (3) D2D network. MHs (e.g., MH A and MH B in Fig. 1) provide opportunistic D2D communication for MS, and connect to nearby WiFi APs or Cellular BSs through WiFi or cellular communication.

The mobile data being received from cloud to MS is divided into a sequence of data units. The data units are predetermined by MNO. Delivering data means transmitting data of size K to MS before deadline D. K is the number of total data units and D is the maximum available time for data transmission. The data delivery is completed when non-transmitted data size k (i.e., k is the size of data that has not been received by MS) is zero before D. Conventionally, without WiFi APs and MHs, MS receives all mobile data through cellular communication. However, in our model, MS has an option to receive parts of the data through nearby WiFi or D2D communication, which may offer higher data rates and lower communication cost.

Upon arrival of a data delivery request from MS, MNO decides whether to transmit data by cellular network or offload it to WiFi and D2D networks according to data characteristics and network performance. The possibility of offloading depends on the delay characteristic (i.e. delay tolerant or not) of mobile data. If data is delay tolerant, MNO can defer data transmission to increase the possibility of offloading. Otherwise (i.e., data is delay sensitive), MNO will have less opportunities to offload mobile data from cellular network. Moreover, if data rates of WiFi and D2D networks are higher than that of cellular network, MNO can shorten the delivery time by cellular data offloading.

The main idea of data offloading is to use delay tolerance of mobile data and mobility of mobile users to seek opportunities to use WiFi and D2D networks.

We assume that a time slot t is long enough for MS to receive at least one data unit from cellular, WiFi or D2D network. An offloading decision (i.e., selecting a network) is made at the beginning of each time slot. The time when offloading decision is determined is denoted by d; it is called decision epoch. Thus, a network is selected at each decision epoch and will be the working network during the time slot.

At each decision epoch, MNO observes the current system states, i.e., the location of MS, the non-transmitted data size (i.e. *data size* $-$ *transmitted data size*), and the number of available MHs. Based on the observed system state, MNO computes the communication cost for available networks. Then, MNO makes an offloading decision of either transmitting data using cellular network or offloading data to other network (i.e., WiFi or D2D network).

In this paper, we propose a Finite Horizon Markov Decision Process (FHMDP) to formulate this problem, with the aim to minimize communication costs and satisfy delay constraints. Markov decision process is a useful model for sequential decision making, where MNO needs to take a sequence of actions (wireless network selection). FHMDP is a Markov decision process with a finite number of decision epochs [27]. Since every data delivery task should be finished before a given deadline, FHMDP will plan data offloading decisions at each decision epoch. FHMDP planning phase can be implemented in remote cloud and ease the heavy burden of complex data offloading management by MS.

Our model aims to offload mobile data as much as possible using WiFi and D2D networks, in order to reduce the communication cost. As a side effect, this will reduce congestion in cellular network, since connection requests to cellular network will decrease, due to alternative wireless networks. It is worth noting that the locations of WiFi APs and the base station are stationary, while MHs are moving around in the coverage area of base station. MHs can be considered as supplementary to WiFi APs because of their mobility.

IV. Problem Formulation

In this section, we formulate the mobile data offloading problem as a FHMDP problem. Table I gives the notations used in the rest of this paper. For each offloading problem, we assume that data of size K needs to be transmitted before deadline D. The system state for a single MS and multiple MHs is defined as $s = (l, u, k, \mathcal{H})$, where l is the location of MS, u denotes data type, k is the size of data to be transmitted, and $\mathcal{H}$ is a set that includes the locations of MHs. MH, which stores the mobile data that MS needs, is called active MH for MS. MNO chooses an action at each decision epoch $d \in \mathcal{D} = \{1, 2, \cdots, D\}$, in terms of the system state at that time.

The state $l \in \mathcal{L} = \{1, 2, \cdots, L\}$ is the grid index, where L is the number of possible grids that MS may reach before D. We assume that cellular network can provide seamless coverage to all the grids. We classify the grids by available WiFi or D2D networks. The grids containing WiFi APs are in $\mathcal{L}_d^2 = \{l \in \mathcal{L}$: *l can access WiFi network*$\}$. The grids where active MHs reside are in $\mathcal{L}_d^3 = \{l \in \mathcal{L}$: *l can access D2D network*$\}$. The grids where both WiFi and active MH exit are in $\mathcal{L}_d^4 = \{l \in \mathcal{L}$: *l can access WiFi and D2D networks* $\}$. The rest of the grids, including grids without WiFi APs and active MHs, are in $\mathcal{L}_d^1$. Since the locations of MHs may be different at each decision epoch, $\mathcal{L}_d^1, \mathcal{L}_d^2, \mathcal{L}_d^3, \mathcal{L}_d^4$ change over time.

$$\mathcal{L}_d^1 \cup \mathcal{L}_d^2 \cup \mathcal{L}_d^3 \cup \mathcal{L}_d^4 = \mathcal{L} \tag{1}$$

$$\mathcal{L}_d^1 \cap \mathcal{L}_d^2 \cap \mathcal{L}_d^3 \cap \mathcal{L}_d^4 = \varnothing \tag{2}$$

The state element $u \in \mathcal{U} = \{1, 2, \cdots, U\}$ represents the mobile data type (e.g. loose delay or tight delay), where U represents the number of different data types that MNO can deliver to mobile users.. We consider that different data types have different delay requirements resulting in different deadlines. To simplify the model, we consider two sets of data types, each of which has different QoS requirements. More specifically, data types (e.g. VoIP) that are delay-sensitive are in set $\mathcal{U}^1$; the other types (e.g. software update) are in set $\mathcal{U}^0$. Thus, $\mathcal{U} = \mathcal{U}^0 \cup \mathcal{U}^1$.

TABLE I: Notations

Symbol	Description
K	size of mobile data to be transmitted
D	deadline for data transmission
$\mathcal{K}$	set of possible data sizes for mobile data
$\mathcal{D}$	set of decision epochs
k	size of mobile data that are not transmitted
d	time for making offloading decision, called decision epoch
$\mathcal{A}$	set of transmission actions for MNO
$\mathcal{U}$	set of mobile data types
a	index of transmission action, denoting a wireless network
u	mobile data type
L	number of grids that MS may pass by
$\mathcal{L}$	set of possible locations of MS
$\mathcal{H}$	set of locations of active MHs
l	index of a grid that MS may stay
μ	probability of MS staying at the same location in two sequential decision epochs, called stable factor
ν_a	data rate for action a
χ_a	price to transmit a data unit for action a

We divide the data, to be transmitted, to K equal portions; the state variable $k \in \mathcal{K} = \{0, 1, \cdots, K\}$ represents the number of data portions still to be transmitted. If $k = 0$ when $d \leq D$, the data delivery process is completed.

There are four actions corresponding to four offloading decisions. At each decision epoch, MNO selects one of the offloading actions for data transmission. Formally, action $a \in \mathcal{A} = \{1, 2, 3, 4\}$: (1) $a = 1$ (waiting action) means that MS will wait for a chance to receive data from WiFi or D2D network; (2) $a = 2$ (cellular action) means that MS will receive data from cellular network; (3) $a = 3$ (WiFi action) means that MS will receive data from WiFi network; and (4) $a = 4$ (D2D action) means that MS can receive data from D2D network. Notice that WiFi action is executed when MS is in WiFi coverage and D2D action is executed when MS can access an active MH.

In our model, we also consider the influence of different mobile data types. For delay sensitive data, we cannot use D2D network to transmit it because of its slow data rate. The action available at location l is defined as $a \in \mathcal{A}(l, u) \subseteq \mathcal{A}$. We define the available actions according to the location of MS and the type of mobile data.

$$\mathcal{A}(l, u) = \begin{cases} \{1, 2\}, & l \in \mathcal{L}_d^1,\ u \in \mathcal{U} \\ \{1, 2, 3\}, & l \in \mathcal{L}_d^2,\ u \in \mathcal{U} \\ \{1, 2, 4\}, & l \in \mathcal{L}_d^3,\ u \in \mathcal{U}^0 \\ \{1, 2, 3, 4\}, & l \in \mathcal{L}_d^4,\ u \in \mathcal{U}^0 \end{cases} \tag{3}$$

We define the action cost function according to the action taken at each time slot (i.e. the period between two decision epochs). The transition cost $c_d(s, a)$ is equal to the action cost function $cost(a)$.

$$c_d(s, a) = cost(a) = \nu_a \chi_a \tag{4}$$

where ν_a and χ_a are, respectively, the network data rate and the price to transmit a data unit for action a (e.g., $\nu_1 = 0$ and $\chi_1 = 0$ for waiting action). The action cost χ_2, χ_3 and χ_4 are incurred by the usage of cellular, WiFi, and D2D networks at each time slot, respectively. The benefit of mobile data offloading is based on the fact that $\chi_3 < \chi_2$ and $\chi_4 < \chi_2$. It means that the price to send data using cellular network is higher than that of using WiFi and D2D networks. The total cost of transmitting data of size K is the sum of costs incurred at each time slot during the total transmission time.

There may be some data transmission tasks that cannot be completed before the deadline. For failed data transmissions (i.e. $k > 0$ when $d > D$), we set the penalty cost function in Eq. (5). It is based on the data type u and the size k of the data not transmitted by the deadline.

$$c_{D+1}(s) = penalty(k, u) = k^{(u+1)} \tag{5}$$

The memoryless mobility pattern of MSs and MHs is defined in Eq. (6). The new location l' depends only on the past location l and has no relation with data type and data size. We design a two dimensions movement pattern. Every mobile user (including MSs and MHs), at each decision epoch, can move from current grid to one of the adjacent grids or stay at the same grid. The probability that mobile user stay at the same grid in two sequential decision epochs is called stable factor, denoted by μ. Alternatively, it can move randomly to a adjacent location with probability $\rho_i, i \in \{1, 2, 3, 4\}$, where i represents one of four possible moving directions (i.e., north, south, east and west). The stable factor μ and the probability of moving direction ρ_i satisfy Eq. (7).

$$P(l'|l) = \begin{cases} \mu, & l' = l \\ \rho_i, & otherwise \end{cases} \tag{6}$$

where

$$\mu + \sum \rho_i = 1, \quad i \in \{1, 2, 3, 4\} \tag{7}$$

Since MSs and MHs may randomly move before the deadline, we are interested in the situation where they can meet (connect) with each other at some other location. The probability that MS m can connect with MH n at decision epoch d and location l is defined as $P_d^m(l) * P_d^n(l)$. $P_d^m(l)$ is defined in Eq. (8); it represents the probability for MS m to stay in location l during decision epoch d. l_m is the initial location of MS before the offloading process.

$$P_d^m(l) = \begin{cases} 1, & \text{if } P_d^m(l) = P_0^m(l_m) \\ \sum\limits_{l' \in \mathcal{L}} P_{d-1}^m(l') \cdot P(l|l'), & \text{otherwise} \end{cases} \tag{8}$$

The system state transition probability is the probability that the system state will go into s' in the next decision epoch if action a is taken at current state s. Since the movement of MS from location l to location l' and MH from h to h' is independent of k, u and transmission action a, we have the following.

$$P(s'|s, a) = P(l'|l) \cdot \prod_{h \in \mathcal{H}} P(h'|h) \cdot P(k'|l, u, k) \tag{9}$$

where

$$P(k'|l, u, k) = \begin{cases} 1, & k' = k - \nu_a \ and \ a \in A(l, u) \\ 0, & otherwise \end{cases} \tag{10}$$

$P(l'|l)$ is the probability that MS will move from location l to location l' and $P(h'|h)$ is the probability that MH will move from location h to location h'. $P(k'|l, u, k)$ indicates that data size k' in next decision epoch is based on current data size k, location l and data type u. Fig. 2 shows illustrated MS state transition graph; the terminal states are those with $k = 0$.

V. Hybrid Offloading Algorithm

In this section, we propose an algorithm, called hybrid offloading algorithm, to compute the optimal offloading policy, according to the movement of each mobile user. Since the offloading decision is based on the location and data type of mobile users, we first consider how these two parameters affect the offloading decision process. A policy π is a set of decisions at each state and decision epoch. It is defined as $a = \pi(s, d)$ in FHMDP. The possible domain for π is denoted by Π. We aim to find the best policy π, which can minimize the overall cost for transmitting data of size F before deadline D. The objective function is defined as follows.

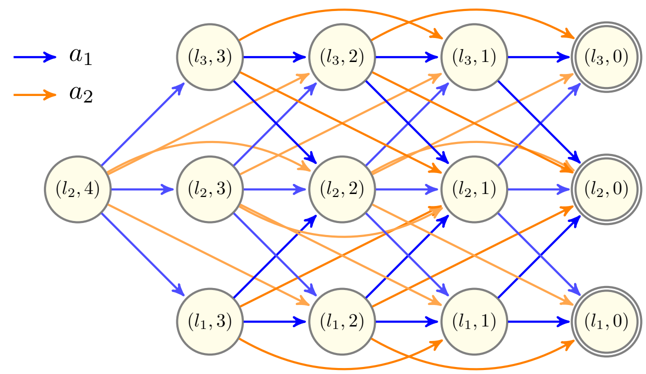


Fig. 2: A sample reduced state transition for MS, where the first component is the location of MS l, and the second component is data size k. Here, $\mathcal{L} = \{l_1, l_2, l_3\}$ and $K = 4$. Action a_1 can transfer 1 data size each time, while a_2 can transfer 2 data size each time. The state with double circle is the terminal state, where $k = 0$, such as state $(l_i, 0)$, $i \in \mathcal{L}$.

$$\min_{\pi \in \Pi} E_s^\pi \left[\sum_{t=1}^{T} c_d(s, \pi_d(s)) + penalty(k, u) \right] \tag{11}$$

We solve problem (11) using our algorithm, called hybrid offloading algorithm (*Algorithm 1*), based on value iteration method [27]. Before presenting our offloading algorithm, we define the value function as follows.

$$V_d^*(s) = \min_{a \in \mathcal{A}(l,u)} Q_d(s, a) \tag{12}$$

where

$$\begin{aligned} Q_d(s, a) &= \sum_{s' \in S} P(s'|s, a)[c_d(s, a, s') + V_{d+1}^*(s')] \\ &= \sum_{s' \in S} P(s'|s, a) cost(a) + \sum_{(l', u, k', \mathcal{H}') \in S} P(s'|s, a) V_{d+1}^*(s') \\ &= \nu_a \chi_a + \sum_{(l', u, k', \mathcal{H}') \in S} P(l'|l) \cdot \prod_{h \in \mathcal{H}} P(h'|h) \\ &\quad \cdot P(k'|l, u, k) V_{d+1}^*(s') \\ &= \nu_a \chi_a + \sum_{l', h' \in \mathcal{L}} P(l'|l) \cdot \prod_{h \in \mathcal{H}} P(h'|h) \\ &\quad \cdot V_{d+1}^*(l', u, (k - \nu_a), \mathcal{H}') \end{aligned} \tag{13}$$

Notice that:(1) the first equality in Eq. (13) shows that expected $Q_d(s, a)$ consists of current cost incurred by taking action a and the future cost when s evolves into s'; and (2) the following equations are derived from Eqs. (4), (9) and (10), respectively.

Our hybrid offloading algorithm consists of two phases: offloading planning phase and offloading phase. In the planning phase, an optimal FHMDP policy is generated. In the offloading phase, MNO takes action from the optimal policy according to current state s. If data type $u \in \mathcal{U}^0$, MNO takes action according to the optimal policy. However, it does not guarantee data delivery before the deadline. If data type $u \in \mathcal{U}^1$, MNO first checks whether current data size can be transmitted using cellular network before deadline (line 18). If the response is yes, MNO will take action according to the optimal policy. Otherwise, MNO will transmit data using cellular network in order to complete data delivery before the deadline. Notice that the function $\kappa(u)$ (line 18) is used to control the delay sensitivity of different data types. A higher delay sensitivity u leads to a higher function value $\kappa(u)$.

Algorithm 1 Hybrid Delayed Tolerant Offloading Algorithm

1: Planning Phase
2: Initialize $\mathcal{H}$ with locations of MHs
3: Initialize $V^*_{d+1}(s)$ with Eq. (5)
4: **repeat**
5:     **for** $d \in \mathcal{D}$ **do**
6:         **for** $s \in \mathbf{S}$ **do**
7:             compute $V^n_d(s)$ using Eq. (12)
8:             compute $rsd^n_d(s) = \|V^n_d(s) - V^{n-1}_d(s)\|$
9:         **end for**
10:     **end for**
11: **until** $rsd^n_d(s) < \epsilon$
12: **return** Best policy π^*
13: Offloading Phase
14: Set $d := 1$ and $k := K$
15: **while** $d < D + 1$ and $k > 0$ **do**
16:     Get the locations of MS and MHs
17:     Set action $a := \pi^*_d(s)$
18:     **if** $k > \nu_2 \times (D - d) \times \kappa(u)$ **then**
19:         $k := k - \nu_2$
20:     **else**
21:         $k := k - \nu_a$
22:     **end if**
23:     $d := d + 1$
24: **end while**

VI. Monotone Policy and Offloading Algorithm

Since the state space becomes extremely large with the increase of deadline D, data size K and the number of MHs, *Algorithm 1* will take more time and resources to solve the problem. In order to reduce the computational complexity for generating the optimal policy, we provide sufficient conditions under which the offloading policy is monotone (non-decreasing or non-increasing) in terms of data size k and decision epoch d, called monotone policy. The monotone policy enables efficient computation due to the existence of threshold structure. Threshold structure has several boundaries between different offloading decisions according to k and d, as shown in Fig. 3 and 4. Thus, instead of generating the optimal actions for all the system state, we only need to determine the threshold states, which can greatly reduce the computational complexity.

The rest of this section is organized as follows. Subsection VI-A presents our assumptions. Subsection VI-B discusses the properties of optimal policy. Subsection VI-C shows the special case where the monotone policy degrades into a single action a^* that does not change with k and d. Subsection VI-D shows the general case where the monotone policy has threshold structure. Subsection VI-E presents an algorithm for generating and executing monotone policy, called monotone offloading algorithm.

A. Assumptions

We make the following assumptions for deriving the monotone policy.

Assumption 1. *The spatial distributions of MS and MHs follow an independent stationary Poisson point process (SPPP) [28, 29].*

At each decision epoch, MS can observe N nearby MHs. N is the number of MHs that MS can establish wireless connections with. The maximum spatial distance that MS can receive data from MH is denoted as R. Based on SPPP assumption for the spatial distribution of MHs, the probability that MS can access n MHs in current decision epoch is calculated by the probability mass function Eq. (14).

$$Ps\{N = n\} = \frac{\pi R^2 \lambda^n}{n!} e^{-\pi R^2 \lambda},\ n = 0, 1, 2, ... \tag{14}$$

where λ is the distribution density of MHs in the system.

Moreover, the probability that MS can access at least one MH in current decision epoch is calculated by the contact distribution function Eq. (15).

$$Ps\{n > 0\} = 1 - Ps\{n = 0\} = 1 - e^{-\pi R^2 \lambda} \tag{15}$$

Since the number of MHs N is distributed as SPPP, we can remove the set of locations of MHs $\mathcal{H}$ out of the system state, i.e., $s = (l, u, k)$.

Assumption 2. *Given u, the penalty function $c_{D+1}(l, u, k)$ in Eq. (5) is non-decreasing with k and satisfies the following relation:*

$$c_{D+1}(l, u, \nu_a) > cost(a) \tag{16}$$

Eq. (16) indicates that MNO should take an action $a \in \mathcal{A}$ at each decision epoch d, since the penalty cost of data with size ν_a at $D + 1$ is larger than the action cost a at $d \in \mathcal{D}$.

Assumption 3. *The costs for cellular, WiFi and D2D networks (χ_2, χ_3 and χ_4) are location independent and satisfies the relation $\chi_3 < \chi_4 < \chi_2$.*

Assumption 4. *The data rates for cellular, WiFi and D2D networks (ν_2, ν_3 and ν_4) are location independent.*

B. Properties of the optimal policy

We discuss some properties of the optimal policy under above assumptions.

Lemma 1. *Given u, the penalty function $c_{D+1}(l,u,k)$ satisfies the following relation:*

$$c_{D+1}(l,u,k) - c_{D+1}(l,u,(k-\nu_a)) \geq c_d(s,a) \tag{17}$$

for all $d \in \mathcal{D}$, $k \geq \nu_a$ and $a \in \mathcal{A}$.

Proof. The penalty cost (defined in Eq. (5)) should be greater than the action cost (defined in Eq. (4)) for the same data size ν_a, which is shown in *Assumption 2*. Otherwise, the action that does not satisfy Eq. (16) can be eliminated from action set $\mathcal{A}$.

Moreover, given u, the penalty cost is a power function with respect to data size k by the definition of Eq. (5). Thus, we obtain Eq. (18) according to the property of power functions. For all $k \geq \nu_a$,

$$\begin{aligned} c_{D+1}(l,u,k) - c_{D+1}(l,u,(k-\nu_a)) \geq& \\ c_{D+1}(l,u,\nu_a) - c_{D+1}(l,u,0)& \\ = c_{D+1}(l,u,\nu_a)& \end{aligned} \tag{18}$$

By Eqs. (18), (16) and the definition of action cost, we get Eq. (17). □

Lemma 2. *The value function $V_d^*(s) = V_d^*(l,u,k)$ is a non-decreasing function with k, $\forall l \in \mathcal{L}, u \in \mathcal{U}, d \in \mathcal{D}$.*

Proof. We prove the result using backward induction. Since $c_{D+1}(s)$ is non-decreasing with k based on *Assumption 2*, $V_{D+1}^*(s) = c_{D+1}(s)$ is non-decreasing with k. Assume that $V_{d'}(s)$ is non-decreasing with k for $d' = d+1, \cdots, D+1$.

$$a^* = \underset{a \in \mathcal{A}(l,u)}{\operatorname{argmin}}\, Q_d(s,a) \tag{19}$$

Based on Eqs. (12), (13), (19) and removing $\mathcal{H}$ out of s, we get

$$\begin{aligned} V_d^*(l,u,k) &= Q_d(s,a^*) \\ &= \nu_{a^*}\chi_{a^*} + \sum_{l' \in \mathcal{L}} P(l'|l) \cdot V_{d+1}^*(l',u,(k-\nu_{a^*})) \end{aligned} \tag{20}$$

By induction hypothesis, $V_{d+1}^*(l',u,(k-\nu_{a^*})$ is non-decreasing with k. Thus, $V_d^*(l,u,k)$ is non-decreasing with k.

□

Lemma 3. *The value function $V_d^*(s) = V_d^*(l,u,k)$ is a non-decreasing function in d, $\forall l \in \mathcal{L}, u \in \mathcal{U}, k \in \mathcal{K}$.*

Proof. We prove the result using backward induction. Based on Eqs. (20), (4) and (5), we get Eqs. (21) and (22).

$$\begin{aligned} V_D^*(l,u,k) &= \nu_{a^*}\chi_{a^*} + \sum_{l' \in \mathcal{L}} P(l'|l) \cdot V_{D+1}^*(l',u,(k-\nu_{a^*})) \\ &= cost(a^*) + penalty((k-\nu_{a^*}),u) \\ &= c_D(s,a) + c_{D+1}(l,u,(k-\nu_{a^*})) \end{aligned} \tag{21}$$

$$V_{D+1}^*(l,u,k) = c_{D+1}(s) = c_{D+1}(l,u,k) \tag{22}$$

Subtract Eq. (22) from Eq. (21), we get the following equation.

$$\begin{aligned} V_{D+1}^*(l,u,k) - V_D^*(l,u,k) = c_D(s,a) +& \\ c_{D+1}(l,u,(k-\nu_{a^*})) - c_{D+1}(l,u,k)& \end{aligned} \tag{23}$$

According to Eqs. (23) and (17) in *Assumption 2*, we obtain Eq. (24).

$$V_{D+1}^*(l,u,k) \geq V_D^*(l,u,k) \tag{24}$$

Assume that $V_{d'}(s)$ is non-decreasing in s for $d' = d+1, \cdots, D$. By induction hypothesis, $V_{d+1}^*(l',u,(k-\nu_{a^*})$ is non-decreasing in d for Eq. (20). Thus, $V_d^*(s)$ is non-decreasing in d. □

Lemma 2 reflects the fact that the expected value is higher when the non-transmitted data size k is larger. *Lemma 3* shows that a larger decision epoch d (i.e. the deadline is closer) results in higher expected cost.

C. Single action monotone policy

In this subsection, we show the special case where the monotone policy degrades into a single action a^* that does not change with k and d.

Definition 1. *Given $l \in \mathcal{L}$, $u \in \mathcal{U}$, an action $a^*_{(l,u)} \in \mathcal{A}(l,u)$ is dominant for MNO if,*

$$Q_d(l,u,k,a^*_{(l,u)}) \leq Q_d(l,u,k,a_{(l,u)}) \tag{25}$$

for all $a_{(l,u)} \in \mathcal{A}(l,u)$, $d \in \mathcal{D}$ and $k \in \mathcal{K}^+$,

where $k \in \mathcal{K}^+ = \mathcal{K} \setminus \{0\}$; $k = 0$ indicates that the data transmission process is finished and thus no action is chosen.

$a^*_{(l,u)}$ is called the dominant action in location l for data with type u. Notice that $a^*_{(l,u)}$ is different from a^* in Eq. (19). $a^*_{(l,u)}$ is the optimal action for all $d \in \mathcal{D}$ and $k \in \mathcal{K}^+$, while a^* is the optimal action for some k and d. Next, we establish conditions under which a dominant action exists.

Theorem 1. *For location $l \in \mathcal{L}^2 \cup \mathcal{L}^4$ with WiFi network and $u \in \mathcal{U}$, if $\nu_2 < \nu_3$ and $\nu_4 < \nu_3$, we obtain a dominant action $a^*_{(l,u)} = 3\,(WiFi)$, for all $d \in \mathcal{D}$ and $k \in \mathcal{K}^+$. The optimal policy is*

$$\pi_d^*(l,u,k) = a^*_{(l,u)} = 3\,(WiFi). \tag{26}$$

Proof. We first prove that $Q_d(l,u,k,3) \leq Q_d(l,u,k,2)$. From Eq. (20), we get

$$Q_d(l,u,k,3) = \nu_3\chi_3 + \sum_{l' \in \mathcal{L}} P(l'|l) \cdot V_{d+1}^*(l',u,(k-\nu_3)) \tag{27}$$

$$Q_d(l,u,k,2) = \nu_2\chi_2 + \sum_{l' \in \mathcal{L}} P(l'|l) \cdot V_{d+1}^*(l',u,(k-\nu_2)) \tag{28}$$

Subtracting Eq. (27) from Eq. (28), we get Eq. (29a). Since $\nu_2 < \nu_3$, let $\nu_3 = \nu_2 + \delta$ and $\delta > 0$. Replacing ν_3 with $\nu_2 + \delta$ in Eq. (29a), we get Eq. (29b).

$$
\begin{aligned}
&Q_d(l,u,k,2) - Q_d(l,u,k,3) \\
&= \nu_2\chi_2 - \nu_3\chi_3 + \sum_{l'\in\mathcal{L}} P(l'|l)\cdot \\
&\quad \Big(V^*_{d+1}\big(l',u,(k-\nu_2)\big) - V^*_{d+1}\big(l',u,(k-\nu_3)\big)\Big) && \text{(29a)}\\
&= \nu_2(\chi_2-\chi_3) - \delta\chi_3 + \sum_{l'\in\mathcal{L}} P(l'|l)\cdot \\
&\quad \Big(V^*_{d+1}\big(l',u,(k-\nu_2)\big) - V^*_{d+1}\big(l',u,(k-\nu_2-\delta)\big)\Big) && \text{(29b)}\\
&> \sum_{l'\in\mathcal{L}} P(l'|l)\cdot\Big(V^*_{d+1}\big(l',u,(k-\nu_2)\big) - \\
&\quad V^*_{d+1}\big(l',u,(k-\nu_2-\delta)\big) - \delta\chi_3\Big) && \text{(29c)}\\
&= \sum_{l'\in\mathcal{L}} P(l'|l)\cdot\Big(\sum_{a\in\mathcal{A}} p_a\delta\chi_a - \delta\chi_3\Big) && \text{(29d)}\\
&\geq \sum_{a\in\mathcal{A}} p_a\delta\chi_3 - \delta\chi_3 && \text{(29e)}\\
&= 0 && \text{(29f)}
\end{aligned}
$$

Notice that: (1) Based on *Assumption 3*, where $\chi_2 > \chi_3$, we get $\nu_2(\chi_2-\chi_3) > 0$ in Eq. (29b). By eliminating $\nu_2(\chi_2-\chi_3) > 0$, we get Eq. (29c); (2) Eq. (29d) is due to *Lemma 2*. Since $(k-\nu_2) \geq (k-\nu_2-\delta)$, we get Eq. (30).

$$V^*_{d+1}\big(l',u,(k-\nu_2)\big) - V^*_{d+1}\big(l',u,(k-\nu_2-\delta)\big) = \Delta \geq 0 \quad (30)$$

where Δ is the cost for transmitting data of size δ; it is defined in Eq. (31).

$$\Delta = \sum_{a\in\mathcal{A}} p_a\delta\chi_a \quad (31)$$

where p_a is the percentage of data size δ transmitted by choosing action a. Except for the waiting action $a = 1$, where $p_1 = 0$, p_a is unknown for other actions. From *Assumption 3*, χ_3 is the minimum cost, we get Eq. (32).

$$\Delta = \delta \sum_{a\in\mathcal{A}\setminus\{1\}} p_a\chi_a \geq \delta \sum_{a\in\mathcal{A}\setminus\{1\}} p_a\chi_3 = \delta\chi_3 \quad (32)$$

By Eq. (29), we have proved that $Q_d(l,u,k,3) \leq Q_d(l,u,k,2)$. Similarly, if $\nu_4 < \nu_3$, we can prove that $Q_d(l,u,k,3) \leq Q_d(l,u,k,4)$. Moreover, since $\nu_1 = 0 < \nu_3$, we obtain $Q_d(l,u,k,3) \leq Q_d(l,u,k,1)$. According to *Definition 1*, $a^*_{(l,u)} = 3\,(WiFi)$ is the dominant action.

$$\pi^*_d(l,u,k) = \operatorname*{argmin}_{a\in\mathcal{A}(l,u)} Q_d(l,u,k,a) = a^*_{(l,u)} \quad (33)$$

□

Based on *Theorem 1*, where the waiting action, cellular action and D2D action are dominated by WiFi action, we obtain the following corollary.

Corollary 1. *Given d, l and u,*

1) *if $a^1_{(l,u)}, a^2_{(l,u)} \in \mathcal{A}(l,u)$, satisfy $\chi_{a^1_{(l,u)}} > \chi_{a^2_{(l,u)}}$ and $\nu_{a^1_{(l,u)}} < \nu_{a^2_{(l,u)}}$, we say that $a^1_{(l,u)}$ is dominated by $a^2_{(l,u)}$.*
2) *If $a^1_{(l,u)} \in \mathcal{A}(l,u)$, $a^2_{(l',u)} \in \mathcal{A}\setminus\mathcal{A}(l,u)$, satisfy $\chi_{a^1_{(l,u)}} > \chi_{a^2_{(l',u)}}$ and $\nu_{a^1_{(l,u)}} < \nu_{a^2_{(l',u)}}$, we say that $a^1_{(l,u)}$ is potentially dominated by $a^2_{(l',u)}$.*

D. General monotone policy

In this subsection, we show the general case where the monotone policy exists. With the assumptions we made on the penalty function and independent date rates, as well as *Lemmas 2* and *3*, we can prove that the monotone policy exits in dimensions k and d. We show that $Q_d(s)$ is superadditive or subadditive in $\mathcal{S}\times\mathcal{A}$ and $\mathcal{D}\times\mathcal{A}$ based on different relationships between data rates for three networks. Then we define the optimal monotone policy $\pi^*_d(s)$ in dimension s and d.

Definition 2. *A real valued function $f_d(s,a)$ is superadditive in $\mathcal{S}\times\mathcal{A}$, if*

$$f_d(s^+,a^+) - f_d(s^+,a^-) \geq f_d(s^-,a^+) - f_d(s^-,a^-) \quad (34)$$

for $\forall s^+, s^- \in \mathcal{S}$ and $\forall a^+, a^- \in \mathcal{A}$, where $s^+ \geq s^-$ and $a^+ \geq a^-$.

Equivalently, we say that $f_d(s^+,a^+) - f_d(s^+,a^-)$ has monotone increasing differences with respect to s. $f_d(s,a)$ is subadditive in $\mathcal{S}\times\mathcal{A}$ if $-f_d(s,a)$ is superadditive.

Given $l \in \mathcal{L}$, $u \in \mathcal{U}$,

$$s^+ \geq s^- \iff (l,u,k^+) \geq (l,u,k^-) \iff k^+ \geq k^- \quad (35)$$

The superadditive function has two properties [30], as defined in *Lemmas 4* and *5*:

Lemma 4. *If $f_1(s,a)$ and $f_2(s,a)$ are superadditive in $\mathcal{S}\times\mathcal{A}$, $h(s,a) = f_1(s,a) + f_2(s,a)$ is superadditive in $\mathcal{S}\times\mathcal{A}$.*

Lemma 5. *If $f(s,a)$ is superadditive in $\mathcal{S}\times\mathcal{A}$, $g(a)$ defined in Eq. (36) is monotone increasing in s.*

$$g(a) = \operatorname*{argmin}_{a\in\mathcal{A}} f(s,a) \quad (36)$$

Theorem 2. *The optimal monotone policy $\Pi^* = \big\{\pi^*_d(l,u,k) = a^*,\ \forall\ l \in \mathcal{L}, u \in \mathcal{U}, k \in \mathcal{K}, d \in \mathcal{D}\big\}$ has threshold structure in both k and d as follows:*

(a) *For location $l \in \mathcal{L}^1$ with only cellular network and $u \in \mathcal{U}$, we get $\mathcal{A}(l,u) = \{1,2\}$ by Eq.(3). There is one threshold for both k and d. That is $\forall d \in \mathcal{D}$,*

$$\pi^*_d(l,u,k) = \begin{cases} 2\,(cellular), & if\ k \geq k^*(l,u,d),\\ 1\,(waiting), & otherwise,\end{cases} \quad (37)$$

and $\forall k \in \mathcal{K}$,

$$\pi^*_d(l,u,k) = \begin{cases} 2\,(cellular), & if\ d \geq d^*(l,u,k),\\ 1\,(waiting), & otherwise.\end{cases} \quad (38)$$

(b) *For location $l \in \mathcal{L}^2$ with cellular and WiFi networks, and $u \in \mathcal{U}$, we get $\mathcal{A}(l,u) = \{1,2,3\}$ by Eq.(3). If $\nu_2 > \nu_3 > \nu_4$, there is one threshold for both k and d. That is $\forall d \in \mathcal{D}$,*

$$\pi_d^*(l,u,k)=\begin{cases}2\,(cellular), & if\ k\geq k^*(l,u,d),\\ 3\,(WiFi), & otherwise,\end{cases} \tag{39}$$

and $\forall k\in\mathcal{K}$,

$$\pi_d^*(l,u,k)=\begin{cases}2\,(cellular), & if\ d\geq d^*(l,u,k),\\ 3\,(WiFi), & otherwise.\end{cases} \tag{40}$$

(c) *For location* $l\in\mathcal{L}^3$ *with cellular and D2D networks, and* $u\in\mathcal{U}^0$*, we get* $\mathcal{A}(l,u)=\{1,2,4\}$ *by Eq. (3). If* $\nu_2>\nu_4$*, there are two thresholds for both* k *and* d*. That is* $\forall d\in\mathcal{D}$*,*

$$\pi_d^*(l,u,k)=\begin{cases}1\,(waiting), & if\ k\leq k_1^*(l,u,d),\\ 2\,(cellular), & if\ k\geq k_2^*(l,u,d),\\ 4\,(D2D), & otherwise,\end{cases} \tag{41}$$

and $\forall k\in\mathcal{K}$,

$$\pi_d^*(l,u,k)=\begin{cases}1\,(waiting), & if\ d\leq d_1^*(l,u,k),\\ 2\,(cellular), & if\ d\geq d_2^*(l,u,k),\\ 4\,(D2D), & otherwise.\end{cases} \tag{42}$$

(d) *For location* $l\in\mathcal{L}^4$ *with cellular, WiFi and D2D networks, and* $u\in\mathcal{U}^0$*, we get* $\mathcal{A}(l,u)=\{1,2,3,4\}$ *by Eq.(3). If* $\nu_2>\nu_4>\nu_3$*, there are two thresholds for both* k *and* d*. That is* $\forall d\in\mathcal{D}$*,*

$$\pi_d^*(l,u,k)=\begin{cases}3\,(WiFi), & if\ k\leq k_1^*(l,u,d),\\ 2\,(cellular), & if\ k\geq k_2^*(l,u,d),\\ 4\,(D2D), & otherwise,\end{cases} \tag{43}$$

and $\forall k\in\mathcal{K}$,

$$\pi_d^*(l,u,k)=\begin{cases}3\,(WiFi), & if\ d\leq d_1^*(l,u,k),\\ 2\,(cellular), & if\ d\geq d_2^*(l,u,k),\\ 4\,(D2D), & otherwise.\end{cases} \tag{44}$$

Proof. We prove the result of *Theorem 2.a*. First, we show that the transition cost $c_d(s,a)$ defined in Eq. (17) is superadditive in $\mathcal{S}\times\mathcal{A}$. From Eq. (17), we get

$$c_d(s^+,a^+)-c_d(s^+,a^-)=\nu_{a^+}\chi_{a^+}-\nu_{a^-}\chi_{a^-} \tag{45}$$

$$c_d(s^-,a^+)-c_d(s^-,a^-)=\nu_{a^+}\chi_{a^+}-\nu_{a^-}\chi_{a^-} \tag{46}$$

By Eqs. (45) and (46), we get

$$c_d(s^+,a^+)-c_d(s^+,a^-)=c_d(s^-,a^+)-c_d(s^-,a^-) \tag{47}$$

Since Eq. (47) satisfies the definition of superadditive function (*Definition 2*), we prove that $c_d(s,a)$ is superadditive in $\mathcal{S}\times\mathcal{A}$.

Then, we show that $V_{d+1}^*(l',u,(k-\nu_a))$ is superadditive in $\mathcal{S}\times\{a^-,a^+\}$, where $a^-=1$ and $a^+=2$.

According to *Lemma 2*, we get Eq. (48). Thus, $V_{d+1}^*(l',u,(k-\nu_a))$ is superadditive in $\mathcal{S}\times\{a^-,a^+\}$.

$$\begin{aligned}&V_{d+1}^*(l',u,(k^+-\nu_{a^+}))-V_{d+1}^*(l',u,(k^+-\nu_{a^-}))\\ &\geq V_{d+1}^*(l',u,(k^--\nu_{a^+}))-V_{d+1}^*(l',u,(k^--\nu_{a^-}))\end{aligned} \tag{48}$$

Based on *Lemma 4*, we obtain that $Q_d(l,u,k,a)$ defined in Eq. (49) is superadditive in $\mathcal{S}\times\{a^-,a^+\}$.

$$Q_d(l,u,k,a)=c_d(s,a)+\sum_{l'\in\mathcal{L}}P(l'|l)\cdot V_{d+1}^*(l',u,(k-\nu_a)) \tag{49}$$

Based on *Lemma 5*, we obtain that the optimal policy $\pi_d^*(l,u,k)$ defined in Eq. (50) is monotone increasing with s.

$$\pi_d^*(l,u,k)=\underset{a\in\{a^-,a^+\}}{\operatorname{argmin}}\ Q_d(l,u,k,a) \tag{50}$$

Thus, $\pi_d^*(l,u,k)$ is a step function of the form Eq. (37). $k^*(l,u,d)$ is a state at which the optimal policy switches from $a^-=1$ to $a^+=2$, called threshold state. Similarly, we can prove Eq. (38) by showing that $Q_d(l,u,k,a)$ is superadditive in $\mathcal{D}\times\mathcal{A}$ by *Lemma 3*.

□

We can derive *Theorem 2.(b)-(d)* by *Corollary 1* and then prove them the same way as *Theorem 2.a*. For example, considering *Theorem 2.b*, where $\chi_3<\chi_4<\chi_2$ (by *Assumption 3*) and $\nu_2>\nu_3>\nu_4$, action 4 is potentially dominated by action 3. This is because that $\chi_3<\chi_4$ and $\nu_3>\nu_4$ when $3\in\mathcal{A}(l,u)$ and $4\notin\mathcal{A}(l,u)$. Notice that the waiting action 1 is used to delay data transmission by seeking better offloading action. However, we don't need to delay now, since action 4 (the only action not in $\mathcal{A}(l,u)$) is potentially dominated by action 3. Moreover, action 2 and action 3 is not dominated by each other. Thus, $\mathcal{A}(l,u)=\{2,3\}$ and there is one threshold in $l\in\mathcal{L}^2$. Since $\chi_3<\chi_2$, we first choose action 3 $(WiFi)$ which has lower cost. When exceeding the threshold $k^*(l,u,d)$ or $d^*(l,u,k)$, action 2 $(cellular)$ which has higher data rate is used, as shown in Eqs. (39) and (40).

The monotone offloading algorithm need to determine all the threshold states of the state space. In order to reduce the search complexity, we make use of the following corollary.

Corollary 2. *For* $\forall l\in\mathcal{L},u\in\mathcal{U}$*,* $i\in\{1,2\}$ *is the index of threshold,*

1) $k_i^*(l,u,d)\geq k_i^*(l,u,d+1),\forall d\in\mathcal{D}$,
2) $d_i^*(l,u,k)\geq d_i^*(l,u,k+1),\forall k\in\mathcal{K}$.

E. Monotone offloading algorithm

We propose the monotone offloading algorithm in order to reduce the computational complexity for large data size or long deadline, compared to hybrid offloading algorithm. By taking advantage of the threshold structure, instead of computing the policy for every system state, we can only calculate the threshold states. The threshold states are calculated in dimension k, which means that the offloading policy is a function of threshold states $\Pi_k^*=\{k^*(l,u,d)=k,\forall\ l\in\mathcal{L},u\in\mathcal{U},d\in\mathcal{D})\}$. We make offloading decisions according to the threshold states.

Algorithm 2 consists of two phases: (1) planning phase: we use *Algorithm 3* to calculate the threshold states (line 7); and (2) running phase: we make the offloading decisions based on the threshold states obtained in the planning phase. At each decision epoch d, the offloading action a is decided according to the MS location l. For location with WiFi coverage (line 17), the optimal action is WiFi offloading; For location with only cellular coverage, the optimal action is determined by one threshold (line 18). For location with D2D coverage (line 19), the optimal action is determined by two thresholds.

Algorithm 2 Monotone Offloading Algorithm

1: *Planning Phase (for $u \in \mathcal{U}^0$)*
2: Initialize $V^*_{d+1}(s)$ with Eq. (5)
3: Initialize $\Pi^*_k = \varnothing$
4: **for** $l \in \mathcal{L}$ **do**
5:     **for** $d := \{D, ..., 1\}$ **do**
6:         **for** $k := \{0, ..., K\}$ **do**
7:             Call *Calculate Threshold States Algorithm*
8:         **end for**
9:     **end for**
10: **end for**
11: **return** Threshold states $\Pi^*_k = \left\{k^*_i(l, u, d)\right\}$.
12: *Running Phase*
13: Set $d := 1$ and $k := K$
14: **while** $d < D + 1$ and $k > 0$ **do**
15:     Get the location of MS as l
16:     Choose action a in terms of current location l.
17:     **if** $l \in \mathcal{L}^2_d \cup \mathcal{L}^4_d$, set $a = 3$ by *Theorem 1*, **end if**
18:     **if** $l \in \mathcal{L}^1_d$, choose action by *Theorem 2.a*, **end if**
19:     **if** $l \in \mathcal{L}^3_d$, choose action by *Theorem 2.c*, **end if**
20:     $k := k - \nu_a$
21:     $d := d + 1$
22: **end while**

Algorithm 3 Calculate Threshold States

1: Calculate threshold states in dimension k at decision epoch d with file type u (for $\nu_3 > \nu_2 > \nu_4$)
2: **if** $l \in \mathcal{L}^1_d$ **then**
3:     $numThreshold = 1$, $a_1 = 2$
4: **end if**
5: **if** $l \in \mathcal{L}^3_d$ **then**
6:     $numThreshold = 2$, $a_1 = 4$, $a_2 = 2$
7: **end if**
8: **for** $i := \{1, ..., numThreshold\}$ **do**
9:     **if** $k \geq k^*_i(l, u, d + 1)$ **then**
10:         Calculate $Q_d(s, a)$, $\forall a \in \mathcal{A}(l, u)$ using Eq. (13)
11:         Set $\pi^*_d(l, u, k) = \text{argmin}_{a \in \mathcal{A}(l,u)} Q^*_d(s, a)$
12:         Set $V^*(s, d) = Q^*_d(s, \pi^*_d(l, u, k))$
13:         **if** $\pi^*_d(l, u, k) == a_i$ **then**
14:             Set $\Pi^*_k = \Pi^*_k \cup \left\{k^*_i(l, u, d) = k\right\}$
15:         **end if**
16:     **end if**
17: **end for**

Algorithm 3 calculates the threshold states for $l \in \mathcal{L}^1_d \cup \mathcal{L}^3_d$. Notice that there is one threshold in $l \in \mathcal{L}^1_d$, two thresholds in $l \in \mathcal{L}^3_d$ and no threshold in $l \in \mathcal{L}^2_d \cup \mathcal{L}^4_d$, as illustrated in Section VII-A. In *Algorithm 3*, we first set the number of thresholds according to l (lines 3 and 6). Then we use a loop to calculate all the possible threshold states $k^*_i(l, u, d)$ at d. Notice that we only consider k that satisfies the inequality (line 9) instead of all $k \in \mathcal{K}$, which can reduce the computation overhead caused by *line 10*. This is because that the threshold states cannot be found in $k < k^*_i(l, u, d + 1)$ by *Corollary 2.1*.

VII. Performance Evaluation

In this section, we evaluate the performance of our proposed approach. In the evaluation, we use the following performance metrics:

- *Total cost.* The total network cost for data transmission.
- *Completion time.* The total time used for data transmission.
- *Offloading ratio.* The percentage of cellular traffic that MNO transmits through WiFi or D2D networks.
- *Time usage percentage (TUP).* The ratio of completion time to the deadline.

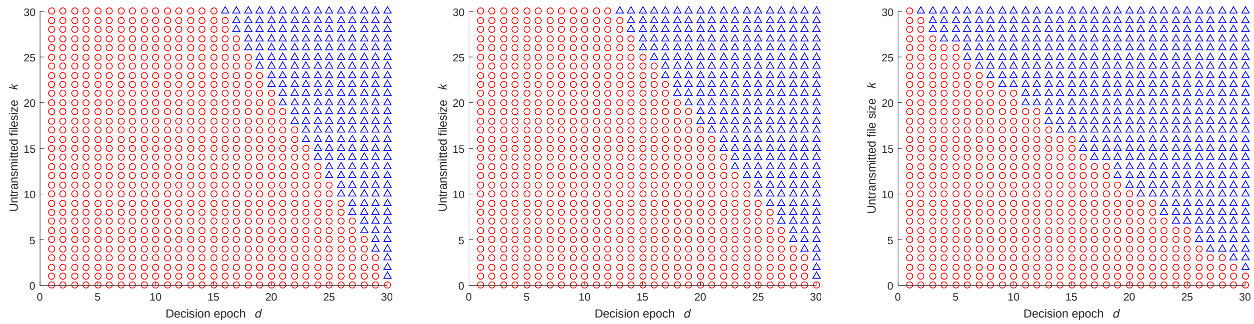
We compare our proposed scheme (we name $D4$) with four benchmark schemes (see Table II). The abbreviation of each scheme includes a digit that indicates the available actions for a system state (i.e., 4 indicates that $\mathcal{A} = \{1, 2, 3, 4\}$ and 3 indicates that $\mathcal{A} = \{1, 2, 3\}$). The benchmark schemes include: (1) optimal delayed WiFi offloading scheme ($D3$) [31]; (2) on-the-spot WiFi offloading scheme ($ND3$) [32]: data transmission is switched between WiFi and cellular networks. WiFi network is used whenever available; and (3) prediction based WiFi and D2D offloading scheme ($ND4$) [6]: WiFi network is used wherever available. Otherwise, D2D network is used when active MH is available and satisfies $k < \nu_2 * (D - d)$,where k is the portion of the data not transmitted yet, d is the decision epoch, D is the deadline for transmitting data and ν_2 is the average data rate for cellular network; (4) no offloading scheme (NO): MS only uses cellular network.

TABLE II: Different offloading schemes

Abbreviation	Schemes
D4	Delayed optimal offloading with 4 actions
D3	Delayed optimal offloading with 3 actions
ND4	Non-Delayed offloading with 4 actions
ND3	Non-Delayed offloading with 3 actions
NO	No Offloading

A. Optimal policy under different network conditions

To illustrate the monotone policy generated by Theorem 2, assume that the data rates for different mobile networks satisfy the relation $\nu_3 > \nu_2 > \nu_4$. Notice that the data rate of WiFi network is higher than cellular and D2D networks and the cost to use WiFi network is lower than cellular and D2D networks. Thus, according to *Corollary 1*, the optimal action for $l \in \mathcal{L}^2_d \cup \mathcal{L}^4_d$ at decision epoch d is 3 *(WiFi)*. The optimal

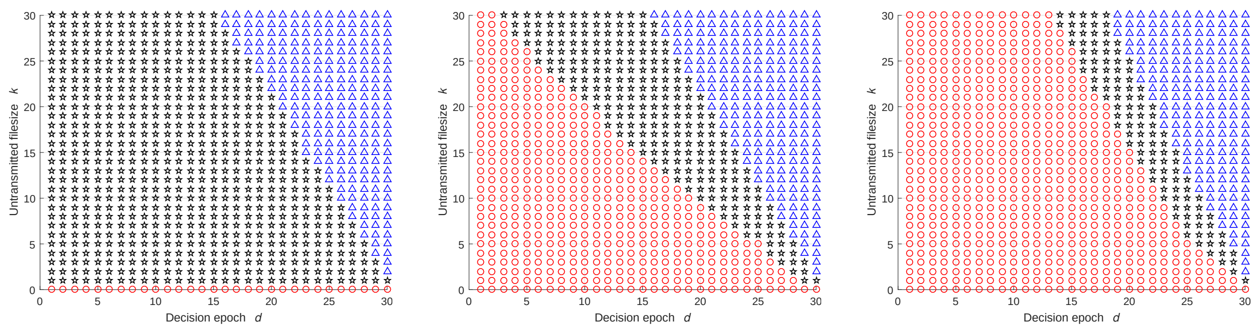


(a) WiFi coverage = 33%, Helper coverage = 0

(b) WiFi coverage = 22%, Helper coverage = 33%

(c) WiFi coverage = 0, Helper coverage = 66%

Fig. 3: Mobile network selection in $\mathcal{L}^1$ with only cellular network, when $\nu_3 > \nu_2 > \nu_4$. The dots and triangles represent the transmission decision of waiting and using cellular, respectively.



(a) WiFi coverage = 0, Helper coverage = 66%

(b) WiFi coverage = 33%, Helper coverage = 66%

(c) WiFi coverage = 66%, Helper coverage = 66%

Fig. 4: Mobile network selection in $\mathcal{L}^3$ with cellular and D2D networks, when $\nu_3 > \nu_2 > \nu_4$. The dots, triangles, and stars represent the transmission decision of waiting, using cellular, and using D2D, respectively.

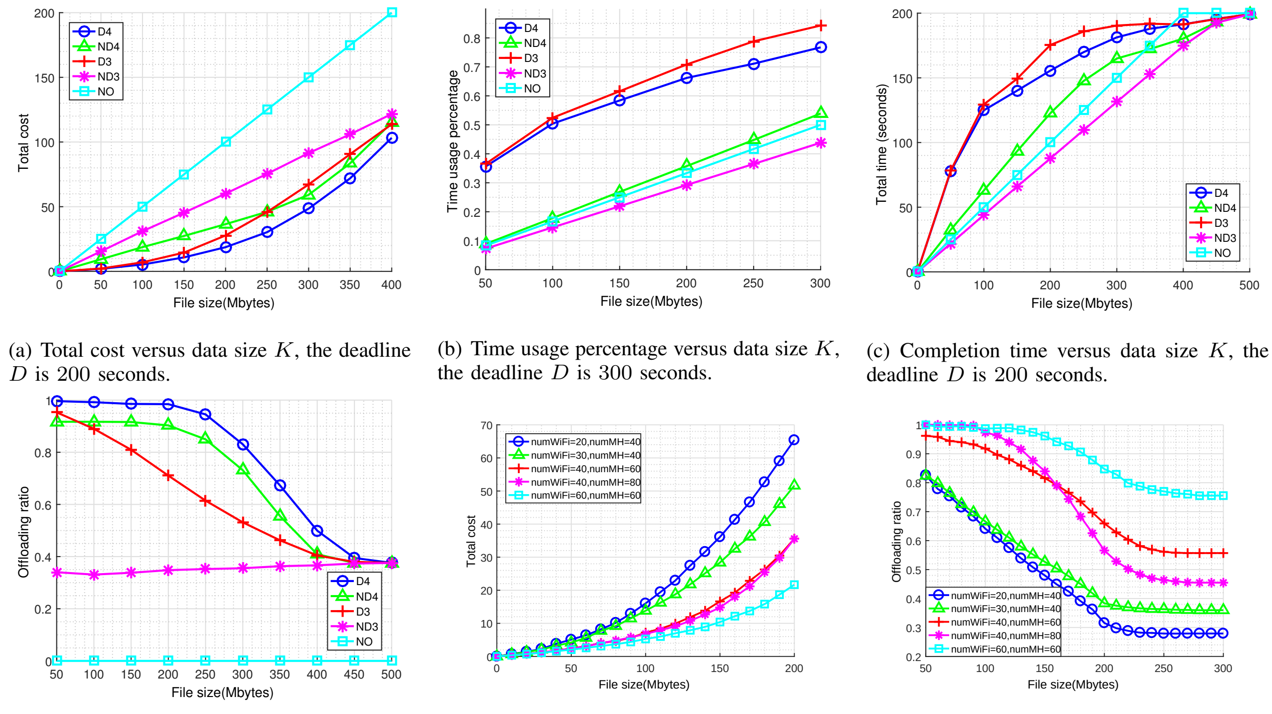
action in $\mathcal{L}_d^1$ and $\mathcal{L}_d^3$, which are based on *Theorem 2* (a) *and* (c), are shown in Figs. 3 and 4, respectively.

Fig. 3 shows the optimal policy in location $l \in \mathcal{L}_d^1$, where MS has only cellular connection. MNO can decide whether to transmit data using cellular network or not. Thus, there are two actions in Fig. 3, waiting action $a = 1$ (denoted by dot) and cellular action $a = 2$ (denoted by triangle). It shows that MNO chooses waiting action when d or k is small. Otherwise, MNO chooses to transmit data using cellular network. For example, in Fig. 3(a), when $k = 10$, the action changes from waiting to using cellular network when $d = 26$. For a larger k, the action changes when d is smaller. We observe that the optimal policy generates a threshold based on k and d. It illustrates that our $D4$ policy will delay the usage of cellular network until the threshold time. This is rational since $D4$ seeks to use other networks (WiFi and/or D2D) before deadline.

We observe that the threshold changes with the knowledge of different WiFi and active MH coverage ratio. With the belief that the coverage ratio of WiFi in Fig. 3(a) is higher than that in Fig. 3(b), MS in Fig. 3(a) has more confidence waiting for WiFi connection in the following decision epochs. Thus, the waiting action area in Fig. 3(a) is larger than that in Fig. 3(b), even though MH coverage ratio in Fig. 3(b) is higher than that in Fig. 3(a). This is because the network setting in Fig. 3(a) has more offloading potential (the size of data can be transmitted using WiFi or D2D network before deadline). Since Fig. 3(c) has the smallest offloading potential, the waiting action area is smaller than that in Figs. 3(a) and 3(b).

Fig. 4 shows the optimal policy in location $l \in \mathcal{L}_d^3$, where MS has cellular and D2D connections. MNO has three actions to choose: waiting action $a = 1$ (denoted by dot), cellular action $a = 2$ (denoted by triangle) and D2D action $a = 4$ (denoted by star). Fig. 4(a) illustrates that MNO decides to transmit data using D2D when d or k is small, instead of waiting (see Fig. 3(c)), with the same knowledge of network setting (i.e., WiFi coverage ratio is 0 and Helper coverage is 66%). Since there is no WiFi available before deadline, MNO chooses to use D2D in order to minimize the overall cost. For a given data size, MNO uses D2D network when d is small. However, with the deadline approaching, the action becomes $a = 2$, since $\nu_2 > \nu_4$. There is one threshold in Fig. 4(a).

Figs. 4(b) and 4(c) show the monotone policy when the coverage ratio for WiFi is 33% and 66%, respectively. There are two thresholds: one is between waiting action area and



(a) Total cost versus data size K, the deadline D is 200 seconds.

(b) Time usage percentage versus data size K, the deadline D is 300 seconds.

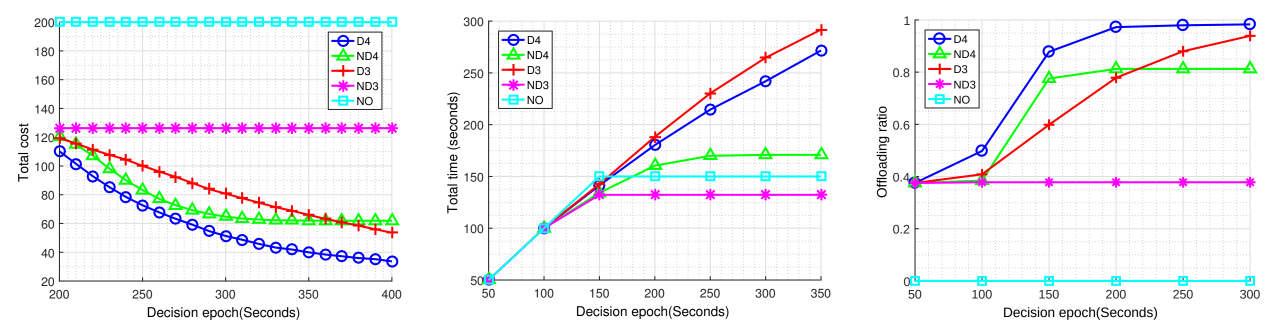
(c) Completion time versus data size K, the deadline D is 200 seconds.

(d) Offloading ratio versus data size K, the deadline D is 200 seconds.

(e) Total cost versus data size K, the deadline D is 100 seconds.

(f) Offloading ratio versus data size K, the deadline D is 100 seconds.

Fig. 5: Performance comparison with fixed deadline.



(a) Total cost versus deadline D, data size K is 400 Mbytes.

(b) Completion time versus deadline D, data size K is 300 Mbytes.

(c) Offloading ratio versus deadline D, data size K is 300 Mbytes.

Fig. 6: Performance comparison with fixed data size.

D2D action area; another is between D2D action area and cellular action area. Compared with two actions (D2D and cellular actions) shown in Fig. 4(a), additional waiting action occurs in Figs. 4(b) and 4(c) with the knowledge of potential WiFi offloading; the WiFi coverage ratio is nonzero in Figs. 4(b) and 4(c). Fig. 4(b) illustrates that MNO chooses waiting action when d or k is small. D2D and cellular networks are used when d and k increase, which ensures that data transmission will be completed before deadline. Both D2D and cellular action areas in Fig. 4(c) are smaller than those in Fig. 4(b), while the waiting action area in Fig. 4(c) is larger than that in Fig. 4(b); this can be explained by the fact that there are more WiFi APs in the case of Fig. 4(c).

B. Performance comparisons among different schemes

We evaluate the performance of $D4$ against four existing schemes (see Table II) with different moving traces generated randomly according to our memoryless mobility pattern. We set the stable factor $\mu = 0.6$ [31]. All locations of WiFi APs and MHs are generated randomly in order to evaluate the efficiency of our scheme. The data rates of WiFi, cellular and D2D networks are defined as $\nu_2 = 16$ Mbps, $\nu_3 = 24$ Mbps and $\nu_4 = 8$ Mbps, respectively, which is a rational setting based on [4, 33].

Similar to [31], we set the cellular unit cost $\chi_2 = 1$ as the baseline. We set the unit cost for D2D and WiFi networks in terms of the reserve price (i.e., the price that MNO is willing to pay at most for offloading one data unit) [8], where $\chi_3 = [0.05, 0.08]$ and $\chi_4 = 0.2$. The cost is set by MNO. If MNO sets a high χ_4 for D2D network, MHs will get high rewards and thus will be willing to help in data offloading. In our evaluation, we set $\chi_3 = 0.08$ and $\chi_4 = 0.2$.

1) Performance comparison with fixed deadline: We compare the schemes under different scenarios with a given deadline D. For evaluation purpose, we simulate the offloading scenario shown in Fig. 1, in which base station is deployed in the center of the region and WiFi APs and MHs are randomly scattered in the grids. The number of locations L is 100 and MS can move randomly in all of the locations.

First, we consider data of small size which can be transmitted before deadline, as shown in Figs. 5(a) and 5(b) . Then, we consider data of larger size that is challenging to transmit before deadline, as shown in Figs. 5(c) and 5(d).

To evaluate the total cost (e.g., the objective function in Eq. (11) of different data sizes, we set the deadline D to 200 seconds and the maximum data size K to 400 Mbytes. Fig. 5(a) shows that the total cost increases with data size. We observe that $D4$ outperforms the other schemes by achieving the lowest total cost for any data size. Note that when $K < 250$ Mbytes, $D3$ outperforms $ND4$; it is not the case when $K > 250$ Mbytes. This can be explained by the fact that $ND4$ can use D2D network to offload more data than $D3$ when $K > 250$ Mbytes, while $D3$ can use delayed WiFi offloading to offload more data than $ND4$ when $K < 250$ Mbytes.

Fig. 5(b) shows that TUP increases with data size, since it takes longer to transmit data of larger size. We observe that TUP of non-delayed schemes (i.e., $ND4$ and $ND3$) is smaller than that of delayed schemes (i.e., $D4$ and $D3$). This is because delayed schemes use additional time to wait for offloading opportunities. TUP of $D4$ is smaller than that of $D3$, since $D4$ can use D2D network to offload mobile data when $D3$ is waiting for another WiFi connection.

Fig. 5(c) shows that completion time increases with data size. We observe that non-delayed schemes (i.e., $ND3$ and $ND4$) achieve short transmission time compared to delayed schemes (i.e., $D3$ and $D4$). This is because the objective of delayed schemes is to use cellular network, only when it is necessary; indeed, they wait for opportunities to use WiFi and D2D networks (in opposition to non-delayed schemes). We also observe that $D4$ outperforms $D3$ because it makes use of D2D network. However, $ND3$ outperforms $ND4$ for any data size. This is because the data rate of D2D network is low. Using D2D network can increase the total time in non-delayed schemes (e.g., $ND3$ outperforms $ND4$) while decreasing the total time in delayed schemes (e.g., $D4$ outperforms $D3$).

Fig. 5(d) shows that the offloading ratio decreases when data size increases except for $ND3$. This is because $ND3$ transmits data based on the location l, without considering current data size k and decision epoch d. Thus, the offloading ratio of $ND3$ cannot change with data size. We observe that the offloading ratio of $D3$ drops rapidly with the increase of data size, while that of $D4$ and $ND4$ drop slowly. This is because $D4$ and $ND4$ use alternative D2D network to offload data. Notice that $D4$ has the highest offloading ratio. We also observe that the offloading ratios for delayed and non-delayed schemes are the same when $K \geq 500$ Mbytes. This can be explained by the fact that 500 Mbytes cannot be transmitted in 200 seconds under the setting used in our simulations. Since all offloading schemes try to complete data delivery before deadline, they use WiFi network wherever possible and cellular network when WiFi network is not available, which is the offloading policy for $ND3$. It means that all other offloading polices (i.e., $D4$, $ND4$, and $D3$) degenerate to the policy used by $ND3$.

In Figs. 5(e) and 5(f), we investigate the impact of the number of WiFi APs (numWiFi) and the number of MHs (numMH) on total cost and offloading ratio for $D4$. We observe that the total cost decreases and the offloading ratio increases with the increase of the number of WiFi APs and MHs.

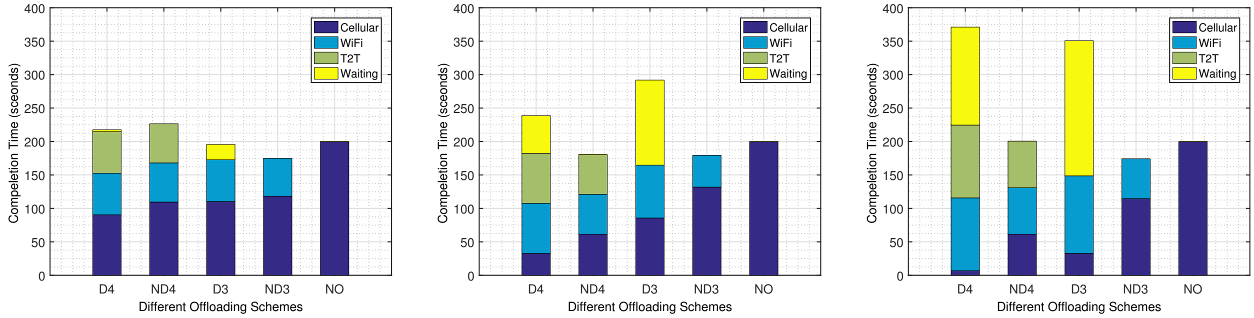
2) Performance comparison with fixed data size: We compare the schemes under different scenarios with a given data size K.

Fig. 6(a) shows that, for delayed schemes (i.e., $D4$ and $D3$) and $ND4$, the total cost decreases when the deadline increases; indeed, larger deadlines give more opportunities (i.e. more time) to look for WiFi and D2D networks to transmit data. We observe that the total cost of $D3$ is larger than that of $ND4$ when $D < 380$ Mbytes. However, the situation changes when $D > 380$ Mbytes. This is because $D3$ uses waiting based strategy for seeking WiFi offloading opportunities; larger deadlines imply more WiFi offloading opportunities. Fig. 6(a) shows that $D4$ incurs the minimum total cost compared to other schemes.

Fig. 6(b) shows that the total transmission time increases with the deadline. We observe that, for $ND3$, the total time does not increase when $D > 150$ seconds. This is because $ND3$ uses on-the-spot strategy and cannot make full use of the delay tolerance. The total time for delayed schemes (e.g., $D3$ and $D4$) increases almost linearly with the deadline; indeed $D3$ and $D4$ use delay time to wait for offloading opportunities. Moreover, $D4$ uses slightly less total time than $D3$ when the deadline increases. However, $D4$ can offload more data than $D3$, as shown in Fig. 6(c). This is because D2D network can be used to transmit data when WiFi connection is not available.

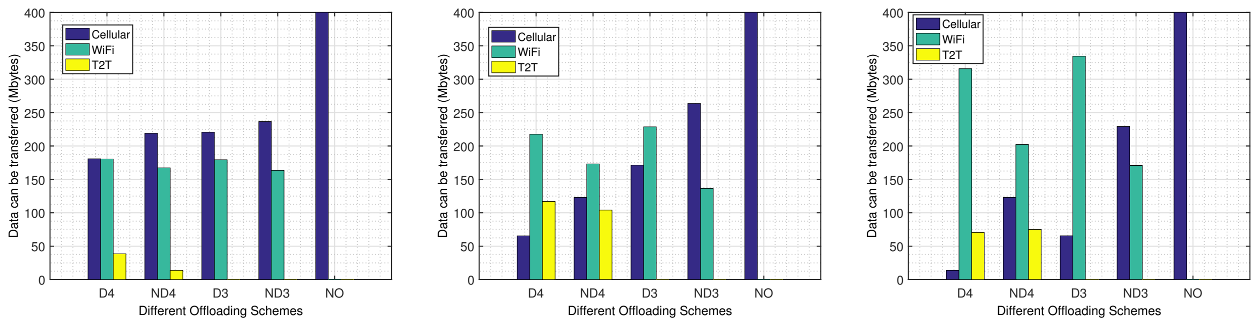
In Fig. 6(c), we observe that offloading ratio increases with the deadline for delayed schemes (i.e., $D3$ and $D4$). This is because delayed schemes can take full advantage of the delay tolerance to seek offloading opportunities through WiFi and D2D networks. We also observe that offloading ratio for $ND3$ does not increase with the deadline, while offloading ratio for $ND4$ increases with the deadline. This is because, for $ND4$, MS has more opportunities to use D2D network as the deadline increases. We conclude that $D4$ achieves the maximum offloading ratio while satisfying data transmission deadline.

3) Simulation Results for Impact of Delay Tolerance: We evaluate the impact of delay tolerance on the transmission time and the amount of data transmitted by different networks, as shown in Figs. 7 and 8, respectively. Three scenarios with low,



(a) $K = 400$ Mbytes, and $D = 200$ seconds. (b) $K = 400$ Mbytes, and $D = 300$ seconds. (c) $K = 400$ Mbytes, and $D = 400$ seconds.

Fig. 7: Total completion time comparison for different schemes, with same data size $K = 400$ Mbytes and different deadline D.



(a) $K = 400$ Mbytes, and $D = 200$ seconds. (b) $K = 400$ Mbytes, and $D = 300$ seconds. (c) $K = 400$ Mbytes, and $D = 400$ seconds.

Fig. 8: Data transmitted comparison for different schemes, with same data size $K = 400$ Mbytes and different deadline D.

middle, and high delay tolerance are considered by setting D to 200, 300 and 400 seconds, respectively. The data size K is set to 400 Mbytes.

In Fig. 7, we observe that higher delay tolerance results in better data offloading performance for delayed schemes (i.e., $D4$ and $D3$) at the cost of longer completion time. To offload the same size of data, less cellular time is used in high delay tolerance scenario. For $D4$, to transmit 400 Mbytes data, 88, 32 and 7 seconds of cellular time are used in the low, middle and high delay tolerance scenarios, as shown in Figs. 7(a), 7(b) and 7(c), respectively. Similar trend applies to $D3$. This is because as D increases, delayed schemes (i.e., $D4$ and $D3$) have more opportunities to use WiFi or D2D network to transmit data to MS, instead of using cellular network.

In Fig. 8, we evaluate the impact of delay tolerance on the amount of data transmitted by different networks. For each scheme, the total amount of data transmitted by different networks is equal to 400 Mbytes. Figs. 8(a), 8(b) and 8(c) shows that for $D4$, with the increase of WiFi data size, cellular data size decreases accordingly. However, D2D data size first increases and then decreases with the increase of deadline D. The reason behind this phenomenon is that when higher delay tolerance is allocated, it is more likely to have more D2D connections or larger D2D data size. However, higher delay tolerance also increases the WiFi data size with lower cost $\chi_3 < \chi_4$. Thus, part of D2D offloading is replaced by WiFi offloading when more WiFi connections are possible. Moreover, compared to other schemes, the cellular data size of $D4$ decreases faster with higher delay tolerance, as shown in Figs. 8(a), 8(b) and 8(c). This demonstrates that the proposed $D4$ can offload more cellular data in practice.

VIII. Conclusion

In this paper, we studied the mobile data offloading problem in MCC. We considered a hybrid offloading network, where data traffic from cellular network can be offloaded to WiFi and D2D networks. Given that WiFi network has high connection speed but low coverage area, and D2D network can help offloading data where WiFi network is not deployed, the hybrid offloading model can effectively reduce data traffic in cellular network. In order to support delay tolerant data transmission, we introduced a hybrid offloading algorithm for delay sensitive and delay tolerant applications. Moreover, we established sufficient conditions for the existence of thresholds in monotone policy and proposed a monotone offloading algorithm which can reduce the computation complexity caused by large data size and long deadline. The simulation results have shown that, compared to existing offloading schemes, our proposed scheme can achieve minimal total cost and maximum cellular traffic offloading ratio.

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