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Author(s): Nadine Abbas, Sanaa Sharafeddine, Hazem Hajj, and Zaher Dawy

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Cost and Energy Aware Dynamic Splitting of Video Traffic in Heterogeneous Networks

Nadine Abbas[1], Sanaa Sharafeddine[1], Hazem Hajj[2], and Zaher Dawy[2]
[1] Lebanese American University, Beirut, Lebanon. Emails: {nadine.abbas, sanaa.sharafeddine}@lau.edu.lb
[2] American University of Beirut, Beirut, Lebanon. Emails: {hh63, zd03}@aub.edu.lb

Abstract—**The vision towards 5G and beyond is to provide remarkable performance enhancements that enable the launch of new services and markets in different industry verticals. Example scenarios of those services include indoor hotspot, broadband access in a crowd, and dense urban; many of which require very high data rates. Traffic offloading and device-to-device cooperation have been leveraged to expand the system capacity and coverage through using heterogeneous network technologies. In this work, we shed the light on the significant gains incurred when predicted short term network performance is factored into network splitting decisions over multiple wireless interfaces, while guaranteeing a desired quality of experience to end users. Accordingly, we allow dynamic use of multiple network interfaces taking into consideration their energy requirement and price models to deliver premium services and minimize the overall energy consumption and total cost. We develop a novel and efficient real-time traffic splitting approach that makes use of predicted bit rate of each network interface in addition to device-to-device cooperation to decide on the amount of video traffic to be delivered on each interface at every time slot. The proposed approach is validated and evaluated under realistic network conditions. Simulation results demonstrate substantial gains in terms of energy consumption, data cost and quality of user experience as compared to multiple alternative solutions.**

I. Introduction

Massive Internet of Things, enhanced mobile broadband, and flexible network operations constitute different 5G usages upon which network requirements are defined [1]. 5G networks are expected to unleash innovative video-based services with high data rates and connection density in various industries such as automotive, public safety, smart cities, and health. In support to achieving the required performance, multiple technologies and mechanisms have spawned as key elements in next generation wireless networks. Heterogeneous networks (HetNets), for example, allow existing networks to be overlaid with additional infrastructure in the form of smaller low-power low-complexity access nodes [2]. Under HetNet deployment, device-to-device (D2D) cooperation may be utilized by user equipments (UEs) in close proximity to deliver data over short range connectivity with low cost and energy expenditures [3] [4]. Such scenarios require UEs to function under seamless operation over multiple wireless networks simultaneously [5] [6]. Figure 1 depicts a HetNet that includes macro cells served by base stations (BS) to cover large geographical areas, and small cells served by low-power access nodes or mobile terminals (MTs). Small cells and D2D cooperation are used to increase capacity in hotspots with high user demand and to cover areas with poor network coverage. With multiple network access options, user-centric

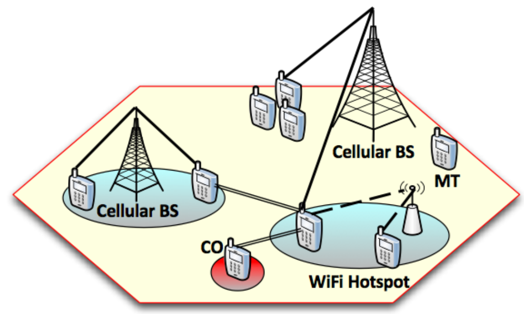

Fig. 1: Heterogeneous network composed of two cellular base stations, one WiFi hotspot, one content owner and mobile terminals with multiple wireless network connections.

content delivery approaches are becoming more challenging and equally attractive. First, the simultaneous utilization of multiple wireless interfaces provides users with higher quality of experience (QoE) at the expense of high cost and energy consumption. Second, mobile devices are powered by limited batteries, the fact, that induces high interest in increasing their lifetime. Nonetheless, users are generally charged differently for using different networks following specific pricing models and data budgets. While data download over cellular networks is generally more costly to users, commercial mobile devices switch to WiFi networks whenever latter networks are available. Recently, mobile devices provide support for auto-switching between WiFi and cellular to avoid poor and unstable WiFi connections.

Research efforts, on the other hand, explored several mechanisms to benefit from the existence of multiple access networks to improve the users' overall QoE by either selecting the best performing network or allowing simultaneous use of multiple networks. The former approach is referred to as network selection while the latter as traffic splitting. The works in [7]–[9] focus on network selection techniques, which make use of a single network at one time. For example, the work in [7] addresses the problem of access network selection by modeling it as a repeated stochastic game to decide on one network for each user in a way to maintain a balanced load among all networks. Regarding traffic splitting, the work in [10] aims at minimizing delay by optimally splitting traffic over two connections established by the UE, one to a macro cell and another to a small cell. Authors in [11] propose optimized techniques to simultaneously utilize multiple wireless interfaces for data downloading and video streaming and demonstrate high performance gains through experimental results.

In [12], dynamic traffic splitting techniques are proposed for video services using WiFi and cellular networks to maximize user experience under energy and delay requirements. The work in [13] leverages the existence of multiple interfaces to support ultra reliable low latency communications and studies the resulting trade-off between reliability and latency. Only few research works jointly address data offloading through multiple interfaces and cost of downloading data. In [14], the problem aims at maximizing user satisfaction in the existence of WiFi and cellular networks while minimizing the incurred benefit loss of both network operators. A network pricing model is developed in [15] to be used by network operators that utilize licensed and unlicensed spectrum in handling the growing traffic demand.

Unlike existing literature, we address the problem of user-centric real-time traffic splitting in D2D heterogeneous networks taking into account predicted short term network performance, energy consumption, and download monetary cost. We propose an efficient traffic splitting algorithm that ensures a desired QoE for video on demand delivery and minimizes energy consumption and data cost over multiple networks. In the sequel, data cost refers to the data cost or price incurred on the user when utilizing a given network for data download. We first develop a utility function to decide on the amount of data to be transmitted on the available interfaces at every time slot, while maintaining a minimum level of user satisfaction. The proposed approach does not require any intervention from the network and/or service operator nor changes to the cellular and WiFi standards, and can autonomously run in the background at the user's device side.

This paper is organized as follows. The system model is presented in Section II. The proposed cost-energy traffic splitting with desired QoE (TS-CE) approach is presented in Section III. Performance results are presented and analyzed in Section IV. Finally, conclusions are drawn in Section V.

TABLE I: Main parameters and variables

Parameters	
I	Number of available networks
T_{s}	Time slot duration
N	Number of time slots for future prediction
S_{v}	Video size
R_{v}	Video bit rate
S_{p}	Packet size
i	Interface index with $i \in [1, ..., I]$
j	Time slot index with $j \in [t, ..., t+N-1]$
$\phi_{i,j}$	Data cost per packet at time slot j over network i
$R_{i,j}$	Estimated transmission rate at time slot j over network i
$\mathfrak{C}_{i,j}$	Maximum allowed number of packets to be transmitted over interfaces i at time slot j
$\Psi_{i,j}$	Energy consumption at time slot j over network i
$P_{i,j}$	Power consumption for receiving over network i at time slot j
Φ	Total data cost over I interfaces and N time slots
Φ_{max}	Maximum data cost over N time slots
Ψ	Total energy consumption over all interfaces for N time slots
Ψ_{max}	Maximum energy consumption over all interfaces for N time slots
T_{m}	Minimum required of buffered video seconds
D_{m}	Minimum required of buffered video packets $D_{\text{m}} = \lceil \frac{T_{\text{m}} R_{\text{v}}}{S_{\text{p}}} \rceil$
D_{b}	Number of packets buffered
$\mathfrak{N}_j$	Number of packets needed to be downloaded to prevent stalling at time slot j
Decision Variables	
$D_{i,j}$	Number of packets to be downloaded over network i at time slot j. $\mathbf{D}$ is a matrix of size $I \times N$

II. System Model

We consider a D2D cooperative heterogeneous network where a user can download data, either from the base stations (BSs) and access points (APs) over long range (LR) wireless technologies (such as WiFi or 4G/5G), or from other MTs using short range (SR) wireless technologies (such as LTE-Direct, WiFi-Direct, Bluetooth or WiFi ad hoc mode). As shown in Figure 1, a mobile device can use multiple wireless interfaces to download data simultaneously from BSs, APs, content owners (COs), which are mobile terminals that already have the data content cached, and other peer mobile terminals.

We consider I wireless interfaces available to the user to download data for on-demand video streaming and assume a slotted time domain with T_{s} time slot duration. We consider a given video streaming at R_{v} and is divided into data packets with a fixed size of S_{p} bits. We aim at deciding on the amount of data packets $D_{i,t}$ to be downloaded over every interface i at time slot t. For an informed decision, we utilize bitrate predictions of every network for the next N time slots. Accordingly, at every time slot t, the transmission rates $R_{i,j}$ (in bps), data cost $\phi_{i,j}$ (in USD), energy consumption $\Psi_{i,j}$ (in Joules) over every network i at time slot j (with $j \in [t, ..., t+N-1]$) should be estimated for the next N time slots. The amount of data to be transmitted over the next N interfaces will then be determined and updated based on the dynamic system variations to provide an optimized balance among cost, QoE, and energy consumption. Table I summarizes the system parameters and decision variables.

III. Cost and Energy-Aware Traffic Splitting with Minimum QoE

In this section, we present our proposed user-centric traffic splitting approach with cost-energy tradeoffs while maintaining a minimum quality of experience level. The proposed approach hereinafter is referred to as TS-CE. The main decision of TS-CE is to determine the amount of data to be delivered over every existing wireless interface in a way that minimizes the total data cost and energy consumption while reducing video stalling events to maintain a desired quality of experience. Accordingly, we define the decision variable $D_{i,j}$

as follows:

- $D_{i,j}$: represents the number of packets to be downloaded over network i at every time slot j, with $i \in [1, ..., I]$ and $j \in [t, ..., t+N-1]$.

One main factor in TS-CE decision is the predicted performance of each interface over a short term period specified by N time slots. It follows that the amount of data $D_{i,j}$ to be transmitted over every interface i for the next N time slots should be determined. Therefore, we represent all decision variables $D_{i,j}$ for N time slots by a matrix $\mathbf{D}$ of size $I \times N$.

A. QoE and Link Capacity Constraints

The traffic splitting problem is subject to several constraints such as bandwidth capacity limitations and minimum level of quality of experience.

- *Maximum link capacity bandwidth*: The number of packets $D_{i,j}$ to be transmitted over interface i at every time slot j should be less than or equal to the interface bandwidth capacity. We define $\mathfrak{C}_{i,j}$ to be the maximum number of packets to be downloaded over interface i at time slot j and can be computed as follows:

$$\mathfrak{C}_{i,j} = \left\lfloor \frac{R_{i,j} \cdot T_{\text{s}}}{S_{\text{p}}} \right\rfloor \tag{1}$$

- *Minimum quality of experience level*: The requested data packets should arrive at the user end before a buffer underflow occurs. Accordingly, the amount of data to be downloaded at every time slot j should be greater than the minimum required number of video data packets $\mathfrak{N}_j$ which can be estimated based on (2). $\mathfrak{N}_j$ depends on the video rate R_{v}, time slot duration T_{s}, packet size S_{P}, data packets buffered D_{b} and the minimum required video data packets buffered D_{m}.

$$\mathfrak{N}_j = D_{\text{m}} + j \cdot \left\lceil \frac{R_{\text{v}} \cdot T_{\text{s}}}{S_{\text{p}}} \right\rceil - D_{\text{b}} - \sum_{k=t, j \neq t}^{j-1} \sum_{i=1}^{I} D_{i,k} \tag{2}$$

In case the bandwidth capacity $\mathfrak{C}_j$ defined in (3) over all the interfaces I, at time slot j, is less than the required number of data packets, the device needs to fully utilize all the interfaces bandwidth simultaneously to guarantee the highest quality of experience.

$$\mathfrak{C}_j = \sum_{i=1}^{I} \mathfrak{C}_{i,j} = \sum_{i=1}^{I} \left\lfloor \frac{R_{i,j} \cdot T_{\text{s}}}{S_{\text{p}}} \right\rfloor \tag{3}$$

B. Cost and Energy Models

To account for cost and energy expenditures, we define our cost and energy models.

- *Cost model*: In our work, we consider Φ the total data cost which the user pays to download data over I interfaces during N time slots. Accordingly, the total cost can be expressed as follows:

$$\Phi = \sum_{i=1}^{I} \theta_i \tag{4}$$

where θ_i is the cost spent when downloading data over interface i. Assuming usage-based pricing charges, users are charged in proportion to the amount of data consumed. The work can be easily extended to apply for other pricing models such as tier-based models. Accordingly, θ_i can be represented as follows:

$$\theta_i = \sum_{j=t}^{t+N-1} \phi_{i,j} \cdot D_{i,j} \tag{5}$$

where $\phi_{i,j}$ is the data cost per packet at time slot j over network i.

- *Energy consumption*: We consider Ψ as the total energy consumed by the mobile device and its peer devices to receive and transmit data. Ψ_1 represents the energy consumed by the mobile terminal, denoted as MT0, to receive data over I interfaces during N time slots. Ψ_2 represents the energy consumed by peer mobile terminals to download data and forwards it to MT0. Accordingly, Ψ can be expressed as follows:

$$\Psi = \Psi_1 + \Psi_2 \tag{6}$$

where

$$\Psi_1 = \sum_{i=1}^{I} \sum_{j=t}^{t+N-1} P_{i,j} \cdot \frac{D_{i,j} \cdot S_{\text{P}}}{R_{i,j}} \tag{7}$$

In case of D2D cooperation, MT0 downloads data from a peer MT k, which can be (1) a content owner, which has the data cached, or (2) a master device, which downloads data using WiFi or cellular and forwards it to MT0. In our work, we assume the master device downloads data with a rate R'_i higher than the forward transmission rate $R_{i,j}$ to MT0 over interface i. Accordingly, MT k consumes $P_{\text{rt},i}$ to download and transmit data to MT0, and $P_{\text{t},i}$ to transmit data to MT0.

$$\begin{aligned} \Psi_2 = &\sum_{i=1}^{I} \beta_i \cdot P_{\text{rt},i} \cdot \frac{\sum_{j=t}^{t+N-1} D_{i,j} \cdot S_{\text{P}}}{R'_i} + \\ &+ \sum_{i=1}^{I} \beta_i \cdot P_{\text{t},i} \cdot \sum_{j=t}^{t+N-1} D_{i,j} \cdot S_{\text{P}} \cdot \left(\frac{1}{R_{i,j}} - \frac{1}{R'_i} \right) \end{aligned} \tag{8}$$

where β_i is an input binary decision variable indicating whether the interface i is a short range connectivity and used for D2D cooperation.

C. TS-CE Utility Function

Our aim is to minimize the total data cost Φ while keeping the energy consumption Ψ low, over the next N time slots. Accordingly, more data should be sent over the more efficient links providing tradeoff between energy consumption and data cost. In order to measure the efficiency of every interface i at every time slot j, we propose a cost-energy tradeoff utility function $U_{i,j}$ expressed as follows:

$$U_{i,j} = \alpha \frac{\phi_{i,j} \cdot d}{\Phi_{\text{max}}} + (1-\alpha) \frac{P_{i,j} \cdot d \cdot S_{\text{p}}}{R_{i,j} \cdot \Psi_{\text{max}}} \tag{9}$$

$U_{i,j}$ represents the performance of interface i at any time slot j while downloading a fixed number of data packets d in terms of cost and energy. The aim is to send data over the interface i at time slot j providing minimum utility $U_{i,j}$. α is a weighting factor indicating the tradeoff between cost and energy consumption. Φ_{max} and Ψ_{max} are the maximum cost and energy that may be consumed, respectively, when d data packets are downloaded, and can be expressed as follows:

$$\Phi_{\text{max}} = \max(\phi_{i,j}) \cdot d \tag{10}$$

$$\Psi_{\text{max}} = \max\left(\frac{P_{i,j}}{R_{i,j}}\right) \cdot d \cdot S_{\text{p}} \tag{11}$$

D. TS-CE Proposed Approach

Based on a required video on demand streaming quality, the proposed TS-CE approach provides real-time decisions for traffic splitting over i available interfaces every time slot t with duration T_{s}. Algorithm 1 details the steps of the algorithm to achieve minimized energy and data cost expenditure. For every time slot t, we compute the needed packets $\mathfrak{N}$, the transmission rates, links capacity, and utility matrix U. The efficiency of using interface i at time slot j is quantified using the utility $U_{i,j}$ in providing tradeoff between cost and energy consumption. For every time slot j, with $j \in [t, t+1, ..., t+N-1]$, we select (i, k) the combination of interface i and time slot k with $k \in [1, ..., j]$, providing the minimum utility function $U_{i,k}$. We repeat the process till the needed packets at time slot j are satisfied or the links reached their maximum capacity. We then repeat the process for all j to find the number of packets $D_{i,j}$ to be downloaded over all the interfaces through the next N time slots. We then consider $D_{i,1}$ as the amount of data to be transmitted over interface i for the next time slot t. We repeat the process for every time slot t until the video data is fully downloaded.

To illustrate the solution of the TS-CE approach, we consider an example composed of MT0, the user of interest, cellular base stations, WiFi hotspot, and one peer MT device as presented in Figure 2. MT0 aims at downloading a video with rate R_{v} of 2 Mbps using multiple wireless interfaces simultaneously. We assume the video data is divided into fixed size packets composed of 11680 bits, the time slot duration is 1 second, which corresponds to 172 packets of video data. In our case model, we assume that a time slot t, the data buffered D_{b} is 450 packets, and the minimum required buffered data D_{m} is 516 packets which corresponds to 3 seconds of playing video data. The traffic splitting decision takes into consideration three slots ahead ($N = 3$). Accordingly, MT0 needs to download in total 582 data packets during the next three time slots, with a minimum cumulative of 238 for the first time slot ($j = t$), 410 for the second ($j = t+1$), and 582 packets for the last time slot ($j = t+2$).

The characteristics of the three interfaces are presented in Figure 2. MT0 consumes 1.307, 1.852, and 0.917 Watts while receiving data over WiFi, 3G cellular networks, and Bluetooth when connected to MT1, respectively. The data packet price depends on the network: (a) WiFi network is assumed to be free of charge ($\phi_{1,j} = 0$), (b) cellular network follows a usage-based pricing model with $\phi_{2,j} = 0.016e^{-3}$ USD per packet, and (c) MT1 is charged $\phi_{3,j} = 0.03e^{-3}$ USD per packet if the data content is not cached and should be downloaded from

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Algorithm 1: The proposed multi-objective traffic splitting with cost-energy tradeoffs (TS-CE)

Input:
- Video specifications: size S_{v}, duration T_{v}, video rate R_{v}
- Time slot duration: T_{s}
- Number of time slots ahead considered: N
- Available interfaces: I
- Interfaces specifications: connectivity (e.g., Bluetooth MT/CO, WiFi, cellular), cost per packet (in USD)
- Minimum required of video seconds and data buffered: T_{m} and D_{m}
- Initial video data buffered: $D_{\text{b}}[0] = 0$
- Initial video data downloaded: $Y[0] = 0$
- Initial queue backlog size: $Q[0] = 0$

Output:
-Matrix **D** of size $I \times N$, representing the amount of data to be downloaded over every interface i at time slot j with $j \in [t, t+1, ..., t+N-1]$.
-The number of packets $D_{i,t}$ to be requested to download over every interface i at time slot t, represented by a the first column $D(1:I, 1)$ of the decision matrix **D**

For every time slot t:
1: **Initialize** the matrix **D** to zero matrix of dimensions $I \times N$
2: **Initialize** the needed packets vector $\mathfrak{N}$ of size N based on (2)
3: **Estimate** transmission rates $R_{i,j}$ for every interface i over the next N time slots, i.e., $j \in [t, t+1, ..., t+N-1]$. This will result in a matrix R with dimensions $I \times N$
4: **Compute** the $I \times N$ link capacity matrix $\mathfrak{C}$, where $\mathfrak{C}_{i,j}$ represents the number of packets allowed to be transmitted over interface i at time slot j. $\mathfrak{C}_{i,j}$ can be computed based on (1)
5: **Initialize** the remaining link capacity matrix L to $\mathfrak{C}$, where $L_{i,j}$ represents the remaining data packet capacity allowed to be downloaded over interface i, at time slot j
6: **Compute** the $I \times N$ utility matrix U, where $U_{i,j}$ represents the tradeoff between cost and energy consumption when receiving d packets over interface i at time slot j based on (9)
7: **For** every time slot j, where $j = t, t+1, ..., t+N-1$
  (a) **Sort** the utility functions $U_{i,k}$ with $k = t, ..., j$
  (b) **Consider** the utility functions $U_{i,k}$ with $k = t, ..., j$, and $L_{i,k} > 0$, where $L_{i,k}$ is the remaining link packet capacity allowed to be downloaded over interface i, at time slot k
  (c) **Select** (i, k) the combination of interface i and time slot k providing the minimum cost utility function
  (d) **If** $L_{i,k}$ capacity is greater than the needed packets $\mathfrak{N}_j$
    then the interface i is partially utilized,
      Update $D_{i,k} = D_{i,k} + \mathfrak{N}_j$
      Update $L_{i,k} = L_{i,k} - \mathfrak{N}_j$
      Update $\mathfrak{N}_j = 0$
    else the interface i is fully utilized,
      Update $D_{i,k} = D_{i,k} + L_{i,k}$
      Update $L_{i,k} = 0$
      Update $\mathfrak{N}_j = \mathfrak{N}_j - L_{i,k}$
      Consider the next interface i providing the lowest utility function, with $k = 1, ..., j$, and $L_{i,k} > 0$
      Repeat process 7 (c) to (d) until $\mathfrak{N}_j = 0$ or all available interfaces I are fully utilized
    end if
  (e) **Repeat** process 7 (a) to (d) for all j.
8: **Consider** $D_{i,1}$ as the amount of data to be transmitted over interface i for the next time slot t
9: **Update** total data downloaded $Y[t]$, queue backlog $Q[t]$ and data buffered $D_{\text{b}}[t]$

Repeat process 1-9 for every time slot t until the video data is fully downloaded

Interface 1: WiFi Hotspot			
$P_{1,j}$	1.307 Watts		
j	1	2	3
$R_{1,j}$	1Mbps	1.5Mbps	2Mbps
Interface 2: 3G Cellular Network			
$P_{2,j}$	1.859 Watts		
j	1	2	3
$R_{2,j}$	2Mbps	2Mbps	2Mbps
Interface 3: MT1 D2D Bluetooth			
$P_{3,j}$	0.917 Watts		
j	1	2	3
$R_{3,j}$	2Mbps	2Mbps	2Mbps
$P_{\mathrm{rt},3}$	2.462 Watts		
$P_{\mathrm{t},3}$	1.405 Watts		
$R'_{\mathrm{t},3}$	3Mbps		

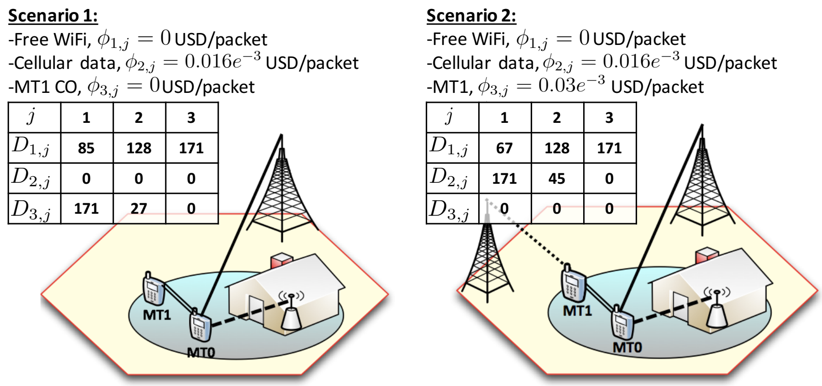

Fig. 2: Toy example illustrating solutions for cost-energy tradeoff traffic splitting TS-CE proposed approach.

the cellular network to provide it to MT0, otherwise, MT1 is a content owner and has the data cached so it can send it to MT0 free of charge. The power consumed by MT1 to receive data over 3G cellular network and forwarding it to MT0 is also considered. We considered two scenarios: (1) MT1 is a CO and has the data cached and (2) MT1 needs to download the data content from a cellular base station and forwards it to MT0. In the first scenario, MT0 downloads most of its data using the free WiFi network to reduce the total cost and energy consumption. When the WiFi data link capacity is reached, the remaining needed data to satisfy the minimum QoE level is downloaded using Bluetooth which is also free of charge. However, Bluetooth consumes higher energy since the power consumed by the content owner to transmit data to MT0 is also considered. In the second scenario, MT1 is no longer a CO, it downloads the requested data from a cellular base station. In this case, MT0 downloads most of its data over WiFi and cellular networks without using D2D cooperation to reduce the total cost and energy while meeting minimum QoE requirements. For both scenarios, using one interface alone, either WiFi or cellular, does not provide the needed data. The use of multiple interfaces was able to meet the minimum level of QoE with tradeoff cost in energy and price. Furthermore, the presence of the CO in the first scenario was able to provide MT0 with its QoE demands, free of charge (0 USD), while reducing its energy consumption by 10%, compared to the second scenario, where MT0 downloads its data using WiFi and cellular networks.

IV. Performance Results and Analysis

In this section, we evaluate the multi-objective traffic splitting (TS-CE) approach under realistic conditions, and compare it with existing traffic splitting techniques, while using multiple wireless interfaces. We first present the simulation setup including parameters obtained using experimental measurements to quantify and analyze the cost-energy tradeoffs of HetNet traffic splitting in various scenarios. We then present simulation results for two wireless interfaces, WiFi and cellular networks, while varying system parameters. We then show the performance enhancement when using multiple wireless interfaces including D2D cooperation.

A. Simulations Setup

We evaluated the performance of our proposed approach using simulations conducted using MATLAB to stream a video using different strategies. In our model, a mobile device downloads data for video streaming application, where the video specifications, such as video size, duration, and frame rate, are obtained as input from the server before the start of the video download. The chosen video has a size of 7 MBytes, a duration of 60 seconds, a frame rate of 25 fps, and an arrival rate of 117 KBytes every second. We assume the user is streaming for 2.5 hours, corresponding to $\sim$1 GB of video data download.

At each time slot of duration 1 second, the proposed approach makes a decision on the data to be downloaded in the next time slot taking energy consumption and data cost into consideration while meeting the minimum QoE requirement. The decision is based on the solution of the TS-CE proposed approach for N time slots ahead. Once data is downloaded, the actual parameters are recorded such as queue size, transmission rate, cost, QoE and energy consumption. The process is then repeated, statistics are updated every time slot until video data is completely downloaded.

We assume the average power consumed is 1.307 Watts for receiving over WiFi, 1.859 Watts over 3G, and 0.917 Watts over Bluetooth. In case of D2D cooperation, the master device streams video frames over a LR interface (e.g., WiFi access point or 3G cellular base station), and relays them to the device in real time over an efficient SR wireless interface (e.g., Bluetooth). Accordingly, the master device consumes 2.462 Watts to simultaneously receive data over 3G and transmit over Bluetooth to its peer device. In case the master device is a CO, it only consumes 1.405 Watts to transmit the data over Bluetooth to its peer device [16] [17].

B. Performance Evaluation

In order to assess the performance effectiveness of the proposed TS-CE traffic splitting approach, we generated results for the following different strategies:

1. *WiFi only* (WO): the user downloads data using WiFi link only.

2. *Cellular only* (CeO): the user downloads data using cellular link only.
3. *Maximum rate network selection* (MaxR-NS): the link providing the higher rate is selected in every time slot.
4. *Traffic splitting using both links simultaneously* (TS-S): the user always uses both links simultaneously to download data.
5. *Traffic splitting with delay-power-QoE balance* (TS-PQ): the user uses one of the following strategies: (1) WiFi alone, (2) cellular alone, (3) traffic splitting, or (4) no transmission. The strategy providing higher delay, power and quality of experience tradeoff utility function is selected on a time slot basis, without considering monetary cost [12].
6. *Traffic splitting with cost-energy balance* (TS-CE): the user splits the data over multiple interfaces based on Algorithm 1, providing a balance between data cost and energy consumption while meeting minimum QoE requirement and taking into consideration the performance of the network within the N future time slots.

C. Simulations Results and Analysis

To compare the performance of the various strategies mentioned in Section IV-B, we evaluated the total energy consumption, data cost and QoE for two case scenarios. In the first case scenario, we considered only two wireless interfaces, WiFi and cellular networks. In the second case, we tested the performance of the proposed approach considering WiFi and cellular networks, in addition to D2D cooperation with multiple mobile terminals.

1) Results considering two interfaces - WiFi and cellular networks: In the first scenario, the transmission rates are modeled following an exponential distribution with a high average rate of 250 KBps. To compare the performance of the various approaches presented in Section IV-B, we quantified the tradeoff between the data cost, the energy consumption and the QoE mean opinion score (MOS) computed based on equation (15) in [12]. In this work, we assume α to be fixed with a value of 0.8, in order to give higher weight to the data cost and T_{m} to be 0 with no requirement on minimum video buffered data.

Figure 3 presents the tradeoff between total energy consumption in Joules versus the data cost in USD for each approach. Figure 4 presents the total energy consumption versus the QoE mean opinion score. The results show low performance for the network selection approaches WiFi only (WO), cellular only (CeO) and maximum rate network selection (MaxR-NS) strategies. For instance, using cellular network only provides low QoE (MOS of 1.02) with high energy consumption (12.4 kJoules) and high data cost (11.8 USD).

The approaches where traffic splitting over multiple wireless interfaces simultaneously is considered provided better performance in terms of user satisfaction, energy consumption and price. TS-PQ presented in [12] aims to provide a balance between QoE, energy consumption and delay while considering one time slot ahead for future prediction, without considering

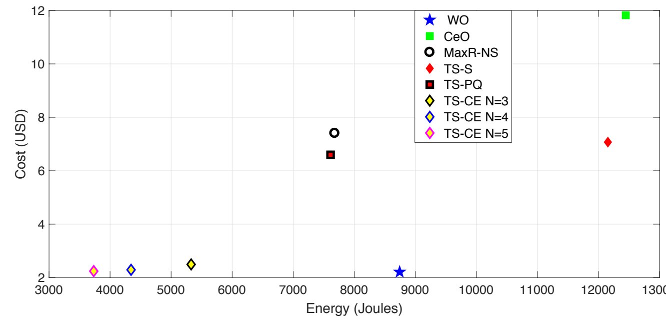

Fig. 3: Total energy expenditure (Joules) and data cost (USD) using WiFi and cellular networks with average rate of 250 KBps.

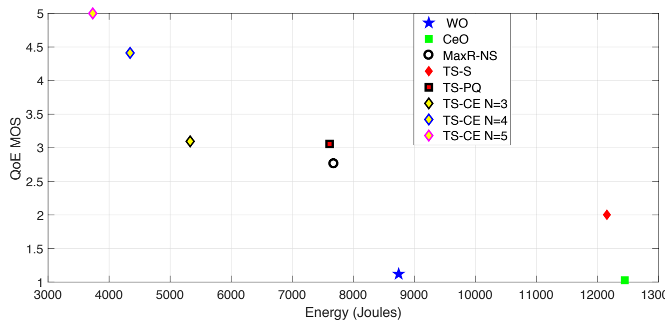

Fig. 4: Total energy expenditure (Joules) and QoE MOS using WiFi and cellular networks with average rate of 250 KBps.

monetary cost for data download. TS-PQ provides higher QoE (MOS 3.05) than using TS-S approach (MOS 2) when using both links simultaneously, while consuming 37.4% less energy, and 6.7% less data cost.

Our proposed TS-CE approach was able to outperform other approaches while providing highest QoE with MOS of 5 (excellent), with more than 51% reduction in energy consumption and 66% reduction in data cost compared to TS-PQ approach. The performance of the proposed approach increases with the increase of N. The QoE increases from 3.09 to 4.41, for $N = 3$ and $N = 4$, respectively, to reach MOS of 5 for $N = 5$. The price decreases from 6.6 USD for TS-PQ to 2.5, 2.28 and 2.24 USD for TS-CE $N = 3$, 4 and 5, respectively. The energy consumption also decreases from 7.6 kJoules to 5.3, 4.3 and 3.7 kJoules for TS-CE $N = 3$, 4 and 5, respectively. The TS-CE monetary cost was close to WiFi since it tended to use WiFi more often due to the high and symmetrical average WiFi and cellular rates.

2) Results considering multiple interfaces - WiFi and cellular networks with D2D cooperation : In order to assess the performance of the use of multiple wireless interfaces simultaneously, we considered the co-existence of the cellular network with multiple WiFi-hotspots and mobile devices. In this part, we assume the transmission rates are modeled following an exponential distribution with a low average rate of 70 KBps. Figures 5 and 6 show the performance of five different data transmission scenarios with different number of interfaces as follows: (1) $I = 2$ (W, C) where two interfaces WiFi and cellular are available to the user, (2) $I = 3$ $(2W, C)$ with

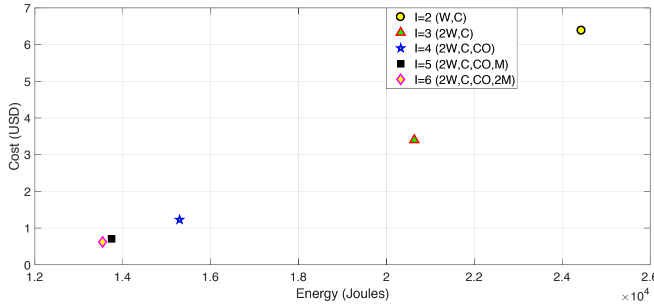

Fig. 5: Total energy expenditure (Joules) and data cost (USD) using multiple wireless interfaces, with R_i average rate of 70 KBps.

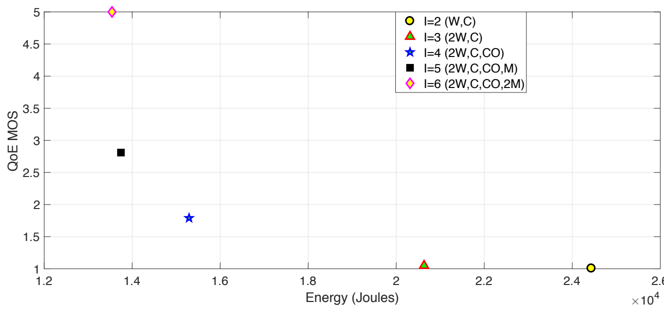

Fig. 6: Total energy expenditure (Joules) and QoE MOS using multiple wireless interfaces, with R_i average rate of 70 KBps.

three interfaces, two WiFi hotspots and one cellular network, (3) $I = 4$ $(2W, C, CO)$ with two WiFi hotspots, one cellular network and a content owner, (4) $I = 5$ $(2W, C, CO, M)$ and (5) $I = 6$ $(2W, C, CO, 2M)$ with five and six interfaces including two WiFi hotspots, one cellular network, a content owner, and one and two master devices, respectively. The master mobile devices are assumed to be downloading their data from a 3G network with $0.002e-3$ USD/packet with a rate of 3Mbps. The results show that increasing the number of devices was able to enhance system performance in terms of increasing QoE while reducing data cost and energy consumption.

The quality of experience increased from 1 (poor) when WiFi and cellular interfaces are used to 5 (excellent) when six interfaces are used. The total cost of transmission and energy consumption were also reduced with the use of D2D cooperation. For instance, when $I = 4$ $(2W, C, CO)$ are used, the mobile device takes advantage of the content owner to reduce the energy consumption and cost while achieving higher throughput. From $I = 3$ to $I = 4$, connecting to a CO was able to reduce the energy consumption by 25.88%, the price by 63.9%, and increase the QoE from 1 to 1.8. To download the same video, using six interfaces simultaneously including D2D cooperation provided 44.58% reduction in energy consumption, 90.25% reduction in data cost while achieving an excellent QoE level of 5, compared to the use of WiFi and cellular interfaces.

V. Conclusions

This paper addressed traffic splitting in D2D cooperative heterogeneous networks, where a user can take advantage of the coexistence of multiple wireless interfaces including D2D cooperation to achieve performance gains. A novel real-time traffic splitting approach was presented allowing dynamic simultaneous use of multiple wireless interfaces providing energy and cost trade-offs while maintaining a minimum quality of experience level. The proposed approach was evaluated using parameters obtained under realistic operational conditions for video on demand streaming applications. Simulation results under various scenarios demonstrated superior performance of the proposed approach as compared to alternative approaches.

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