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Towards Delay-Tolerant Cognitive Cellular Networks

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10.1 Introduction

Over the last few years, we are witnessing a significant increase in the aggregate traffic in mobile networks, which is due to the proliferation of smartphones and Internet applications for mobiles. In this environment, mobile users expect to enjoy ubiquitous wireless Internet experience, which boils down to providing high-capacity connectivity to them anywhere and at any time. For sustainability reasons, operational as well as capital expenditure for mobile operators will need to be reduced. Energy consumption plays a significant role in the overall operational expenditure of a mobile operator. To this end, significant efforts have been recently placed on reducing the overall energy consumption leading to the so-called green networks.

The problem of energy-efficient transmission under delay constraints over wireless networks has been studied extensively over the past few years. Traditionally, the problem of data scheduling has been considered at the medium access control—MAC (i.e., packet) level, which considers short time intervals of the order of few milliseconds at most. Significant volume of research efforts have been placed on energy-efficient data transmission for delay-tolerant applications, especially the trade-off between transmission cost and time delay over wireless networks [1–5]. The work in Ref. [1] deals with the problem of packet scheduling with deadlines within a predefined time window of length T. Based on that, the authors in Ref. [2] explore the energy-efficient packet transmission with individual packet delay constraints, in which a trade-off between flexible energy and delay is analyzed under various individual packet delay constraints and bandwidth efficiencies. In Ref. [3], the authors consider a delay constraint for each packet and reveal the relationship between reliable transmission rate and QoS requirements, while a dynamic programming based algorithm is introduced to acquire throughput maximization and energy minimization according to different channel qualities of a fading

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channel with time constraints [4]. The work in Ref. [5] further investigates the problem of energy-delay trade-offs under dynamic traffic loads and user populations. The target-set selection problem has been studied in the emerging Mobile Social Networks for traffic offloading by delaying the delivery [6]. In Ref. [7], a framework is proposed to investigate the trade-off between the amount of offloaded traffic and the users' delay tolerance over a 3G network.

Meanwhile, many portions of the spectrum are not in use for a significant period of time, thereby implying the existence of plenty of spectrum opportunities that can still be potentially exploited. Hierarchical Cognitive Radio (CR) networks improve spectrum efficiency by allowing the low-priority Secondary Users (SUs) to temporarily seek the wireless spectrum that is licensed to different operators serving Primary Users (PUs) [8]. It should be noted that whenever a PU captures the channel, SUs should be able to sense that the channel is occupied and defer from transmitting or competing unnecessarily for the access to the channel. At the same time, SUs opportunistically use available channels and can be preempted by PUs; in other words, the SU connections would be interrupted by the stochastic nature of the PU traffic. Consequently, the SUs should firstly estimate the channel availability by probability analysis based on PUs' historical traffic information or spectrum sensing. A common technique utilizes traffic characteristics from available long-term observations/statistics [9], and in an alternative approach, an SU selects the operating channel according to the instantaneous sensing results from the channel pre-scanning [10]. In Ref. [11], authors design optimal sensing strategies via a model assuming that the PU transmissions are unslotted as a continuous-time Markov chain while the SUs are slotted to sense the frequency channels. On this basis, the work in Ref. [12] proposes a stochastic multichannel sensing scheme based on traffic information as well as sensing history.

As modern digital devices are equipped with multiple wireless interfaces (such as Wi-Fi, 3G, LTE, and TV White Spectrum TVWS interface), the energy cost on data transfer can potentially differ significantly due to the different operational characteristics of these wireless interface. A detailed study regarding energy consumption in 3G, GSM, and Wi-Fi (802.11b) has been reported in Ref. [13]. Wi-Fi Access Points (APs) are becoming significantly popular, and hereafter the assumption will be that there are a number of APs within the coverage area of a macrocell base station of a cellular network. In cases where the mobility of vehicles and pedestrians can be predicted, the roadside APs evidently improve the average wireless throughput for file delivery by estimating the signal strength of APs along a predicted route utilizing historical RF fingerprints data statistics [14].

In addition to the Aforementioned factors, and as the vacant TVWS spectrum are permitted to be used in several countries, this new available spectrum will unfold new possibilities in data transmission with strong potential to decrease further energy consumption. In Ref. [15], it has been previously shown that the percentage of observed territory with nonzero number of available frequency channels is 64.7% under the ECC rules. In other words, when an SU is in any given location, there is a high probability that at least one frequency channel in TVWS could be available for SU transmission. When the SUs are using 3G cellular networks within the coverage of a TVWS master, it is possible that the SUs would prefer the TVWS connection over the cellular networks in terms of cost, RF coverage, capabilities, and transmission algorithm. However, the cognitive users have to cease wireless transmission immediately and relocate to a new band as soon as a PU appears and requires access to the channel. For the purpose of avoiding PU transmission, the SU nodes could utilize spectrum sensing or query a database that maintains information about the available channels for the details of the local radio environment. The SU connection can utilize the means as sensing or contacting a trusted geospatial database that records the information regarding PUs occupation with a specific location and time duration, prior to message transmission, to determine available spectrum at a given location [16, 29]. In this scenario, to predict the future location and the path of mobility of wireless nodes is another challenging issue in White-Fi networks.

10.1.1 Device-to-Device Communications (D2D)

Device-to-Device (D2D) Communications is a feature that has been introduced in the 3GPP Release 12. D2D communication has been considered as an underlay to an LTE-A cellular network. Devices are allowed to be engaged in direct communication with the network having the control in terms of interference management and resources used [17]. In this context, both the cellular network and the D2D communication use the same LTE resources. Therefore, D2D communications can be considered as an enabler for delay-tolerant networking techniques within the cell, i.e., D2D communication can be used to inteligently delay transmissions and/or relay information to another device or to the base station.

10.1.2 5G Wireless Communications

Currently, mobile operators are trying to cope with the high demand of Internet applications in cellular networks that utilize carrier frequencies that range between 700 MHz and 2.6 GHz. Available spectrum at these carrier frequencies can be deemed as rather limited, and as a result, in order to increase aggregate transmission rates to cope with the ever-increasing demand, there is a need to move higher in the spectrum. To this end, wireless technologies for 5G, or Beyond 4G as it is also called, envision the use of the current very much underutilized millimeter-wave (mm-wave) frequency spectrum ,for example, the use of 28 GHz, 38 Ghz [18], or even the unlicensed 60 GHz as envisioned by the Wireless Gigabit Alliance [19, 20]. Clearly, at these frequencies, signal attenuation is significant, and as a result, high-speed broadband access to the Internet can be considered only for picocells with radius of up to 200 meters. In these scenarios, delaying transmission of elastic user traffic based on the proposed set of solutions can allow for better utilization of the very high speed mm-wave links because it can allow users to refrain transmission until they are within the coverage area. Another important benefit stemming from the use of delaying message transmission until the user is closer to the access point is that in mm-wave spectrum due to the significant path losses, the energy gains that can be achieved by delaying the transmission are even greater compared to current operating frequencies in cellular networks. By inspecting the Friis Law for free-space path loss, it can be seen that when moving from 3 GHz to 30 GHz, path loss increase by 20 dB. Also in these carrier frequencies, the PA has an efficiency of less than 10%; therefore, energy consumption is a key issue. Consequently, by utilizing the elasticity of Internet application and the inherent mobility of users delaying message transmission is well fitted to be utilized in envisioned 5G wireless networks that are based on the use of mm-wave frequency spectrum.

10.2 Scenarios and Applications

Hereafter, the focus is on Internet applications, which can tolerate significant delays without deteriorating the experience of the end user. To this end, the consideration is on highly delay-tolerant traffic, which can tolerate delays that can range from few seconds up to few minutes. Traffic with these characteristics are e-mails, ftp data transfers, updates of social networking portals, message/file exchanged via the File Transfer Protocol (FTP), Rich Site Summary (RSS) feeds, non-real-time video streaming and Operating System (OS) and firmware updates, and updates to social networks, to mention just a few. We can utilize their inherent characteristics to significantly save the energy cost for embedded systems of mobile nodes. Note at this point, and as have been mentioned previously, the increased usage of smartphones and the rich ecosystem of Internet applications are having a severe effect on the recharging cycles of devices due to the increased levels of energy consumption and limitations of battery technology. As the infrastructure of hotspots for Wi-Fi and TVWS (TV White Space) interfaces are becoming ubiquitously available in urban areas, and mobile devices are equipped with multiple air interfaces, they could switch among these networks to seek and use any licensed spectrum bands as long as they do not cause interference to the PUs. In this case, the energy usage in modern devices for transmitting a fixed amount of data could differ drastically due to the significant difference on the achievable data rates on these radios. In addition, channel conditions change according to user mobility and spatial characteristics of the channel. Therefore, predicting the future location and the mobility path of SUs is another challenging issue in White-Fi networks. Furthermore, apart from the availability of the primary channels, the mobile nodes have to compete with other SUs to seek an optimal time duration for wireless transmission. Consequently, a virtual queuing model based on an M/M/K/L system is designed to analyze the optimal population of SUs to be served in the system to minimize the energy consumption of message transmission for the delay-tolerant applications. Wireless nodes (SUs) gather PU traffic information from a historical database in order to predict over a short term the traffic pattern of PUs. In the database server, there are two types of information about primary channels. One is the 24-hour traffic characteristics of different channels across several months [9], and the other is the noise power level in different channels that is updated continuously by the SU devices. An SU has to send a query to the database server for the available channel to transmit. According to the available channel information at the same time slots in previous days and long-term statistics regarding channel availabilities, the database server will certificate the noise power levels by comparing to a threshold. Then, the set of best candidate channels for the inquired SU will be determined.

10.3 Previous Research

For delay-sensitive traffic, there has been an enormous previous research both applied and theoretical within the general area of optimal job scheduling with deadlines [21]. With respect to wireless packet transmission, proposed solutions focus on low-complexity algorithms (to allow real-time implementations) over small timescales, which are technology-specific and depend on the standardized Transmission Time Unit (TTI), which, for example, in UMTS Release-5 has been define to be 2 msec. There has also been significant volume of previous research work on energy-efficient scheduling for wireless packet transmission. The work in Ref. [5] further investigated the problem of energy-delay trade-offs under dynamic traffic loads and user populations. The target-set selection problem has been studied in the emerging Mobile Social Networks for traffic offloading by delaying the delivery of messages [6]. In Ref. [7], a framework is proposed to investigate the trade-off between the amount of offloaded traffic and the users' delay tolerance over a 3G network. Furthermore, a theoretical study of optimal delay-tolerant multi hop transmissions within the cell have been studied in [30].

In accordance with the information of channel utilization, mobile systems can decide which frequency channels to utilize without deteriorating the quality of service of experience of the Primary connections. To this end, queuing theory can be utilized to analyze the wireless transmission in the CR scenario described earlier. In this case, we assume that there are M/M/K/L queue systems for the wireless connection, in which the SU message could be buffered. A preemptive priority queuing system has been utilized to analyze the mean system dwelling time of the SU traffic and the blocking probability for real-time SU connections [22]. In Ref. [23], authors analyze the queue lengths and average queuing delay of the SUs based on Poisson distribution of the SUs. In Ref. [24], a dynamic strategy learning (DSL) algorithm relied on the priority queuing systems including the SUs and the PUs is proposed for the delay-sensitive multimedia applications in order to maximize the user's utility function.

A detailed study regarding energy consumption in 3G, GSM, and Wi-Fi (802.11b) has been reported in Ref. [13]. As Wi-Fi hotspots are becoming very common in recent years, the study in Ref. [25] examined large-size file transmission protocols for vehicle-to-vehicle utilize existing Wi-Fi APs and navigation systems. In the cases where the mobility of vehicles and pedestrians can be predicted, the roadside APs evidently improve the average wireless throughput for file delivery by estimating the signal strength of APs along a predicted route utilizing historical RF fingerprints data statistics [14]. In addition to the above, and as the vacant TVWS spectrum is permitted to be used in several countries, it is without doubt that this new available spectrum will unfold new possibilities in data transmission with strong potential to decrease further the overall energy consumption. In the United States, the unoccupied TVWS has already been filled up with unlicensed users without significant interference to TV viewers, while Ofcom is determined to permit TVWS for unlicensed use by checking with a database in the United Kingdom. Once mobile devices are equipped with multiple air-interfaces allowing them to connect to LTE, WiFi, and TVWS, they could switch among these networks to seek and use any licensed spectrum bands as long as they do not cause interference to the PUs. Prior to wireless transmission via TVWS, digital devices have to sense or contact a trusted geospatial database that records PUs' occupation within a specific location and time duration [16]. In this scenario, predicting the future location and the path of mobility of SUs is another challenging issue in White-Fi networks.

10.4 System Model and Energy Saving Schemes

The ability of performing Adaptive Modulation and Coding (AMC) based on signal quality allows cellular networks to dynamically use higher-order modulation, up to $64QAM$, within strong signal areas and lower-order modulation $QPSK$ in poor signal quality areas for the sake of better signal recovery. To this end, the cell can be separated into n concentric rings of radii $R_i, i = 1, \dots, N$ according to the distance between the wireless device and its serving BS as shown in Figure 10.1. The set of available modulation and coding schemes is denoted by $\{M_{R_1}, M_{R_2}, \dots, M_{R_N}\}$. Consequently, each circular region with distance R_i to the BS corresponds to a different constellation size and coding scheme.

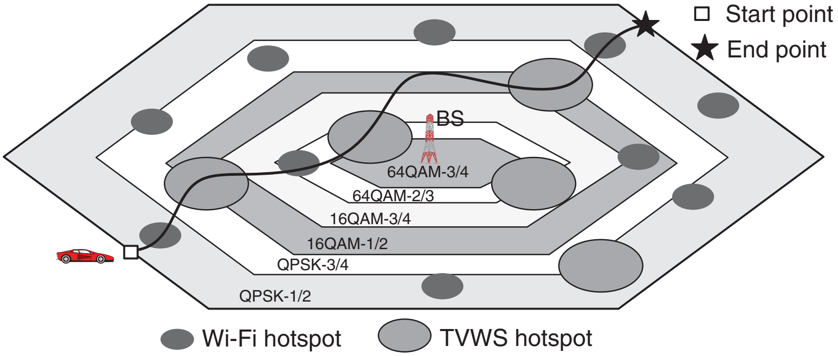

Figure 10.1 The bit rate of mobile users within the coverage of the base station (BS) ring range

Let r denote the coding rate, and r_{BS} be the (Euclidean) distance between the mobile node and the serving BS. Then, the spectral efficiency (bits/s/Hz) is given by Schoenen and Walke [26]:

$$\mathrm{IEC}(r_{\mathrm{BS}}) = r \cdot \log_2(M_{r_{\mathrm{BS}}}) \ \text{bits/s/Hz} \tag{10.1}$$

According to the sector bandwidth of cellular channels, the average sector throughput could be estimated so as to quantify the total capacity through the sector or site coverage. With the aggregate of the user data bit rates and the number of simultaneous concurrency users within the sector, we could determine the network throughput for individual user.

10.4.1 Storage Cost

Broadly speaking, the general architecture of a mobile device (such as smart phones, tablet computers, digital cameras, etc.) can be decomposed into the processing unit (CPU), the local Dynamic Random-Access Memory (DRAM), and flash/hard disk (HDD). When a wireless terminal prepares to transmit data to other nodes, the data has to be ready in the local DRAM. However, if the system decides to wait for a short period to transmit, the data stored in DRAM would be transferred to internal storage devices (e.g., internal NAND flash) or external storage units (e.g., SD card, HDD), which depends on the delay constraints and transmission strategies of mobile applications.

In the numerical investigations, the assumption is that the DRAM has three background power operating modes, namely, the Self Refresh, Precharge Fast Powerdown, and Precharge Standby. Figure 10.2 shows the DRAM power states in different states for wireless transmission. During the transfer process from the DRAM to NAND flash, except for the operation commands, the DRAM would be in the Precharge Standby state for the sake of short wake-up latency, which will consume most power. After the completion of the transfer, the DRAM will enter into a self-refresh state, consuming least power with significantly higher exit latencies. Once the data return to the DRAM for data transfer to the RF module, the DRAM would enter into the Precharge Standby state again. In the mean time, the NAND flash will remain in the idle state except the duration of data transfer between the DRAM and NAND flash.

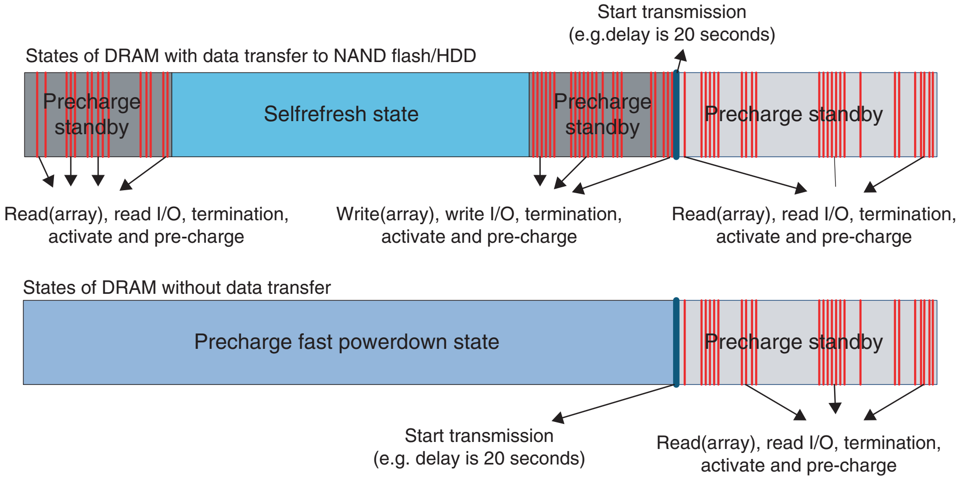

Figure 10.2 Operation and background power state of DRAM

10.4.2 Optimal Stopping Problem

Concerning the energy consumption for wireless data chunk transmission, we can identify the following main sources: (i) the energy required to operate the electronic circuits at the nodes; (ii) the energy consumed for wireless transmission of the data chunk; (iii) the energy consumed to receive the information; and finally, (iv) the energy consumed in DRAM and NAND flash/HDD devices. Based on the aforementioned classification, the inherent trade-offs regarding message delay and energy cost of nodes for wireless transmission can be modeled with an OSP formulation in order to seek optimal solutions for the message transmission scheduling by taking into account available spectrum opportunities for multiple radio interfaces (such as cellular networks, Wi-Fi, and TVWS).

The stopping decision (i.e., the time to transmit the information) would be made based on average channel conditions, delay constraints, and energy consumption. To be more specific, firstly, the policy calculates the data rate (bits/second) at each time slot and finds the optimal time duration that could be utilized for the data transmission of mobile nodes in this time slot, thereby fixing the data length to be transmitted in this time slot. Secondly, this policy calculates the energy cost at all of the candidate stopping time slots from the initial location along the route of vehicle. Finally, the policy should make sure that all of the messages will be transmitted to the BS before the (hard) time deadline. The policy compared all the schemes that launch the message transmission at different time slots, finding the scheme with optimal trade-off between energy cost and time delay under deadline constraints.

10.4.3 Optimal Number of Users

In this section, we turn our focus on the SU message competition without competing PU connections. Figure 10.3 gives an example of the physical queues for the case of K frequency channels and N concentric rings with different modulation and coding schemes. When the

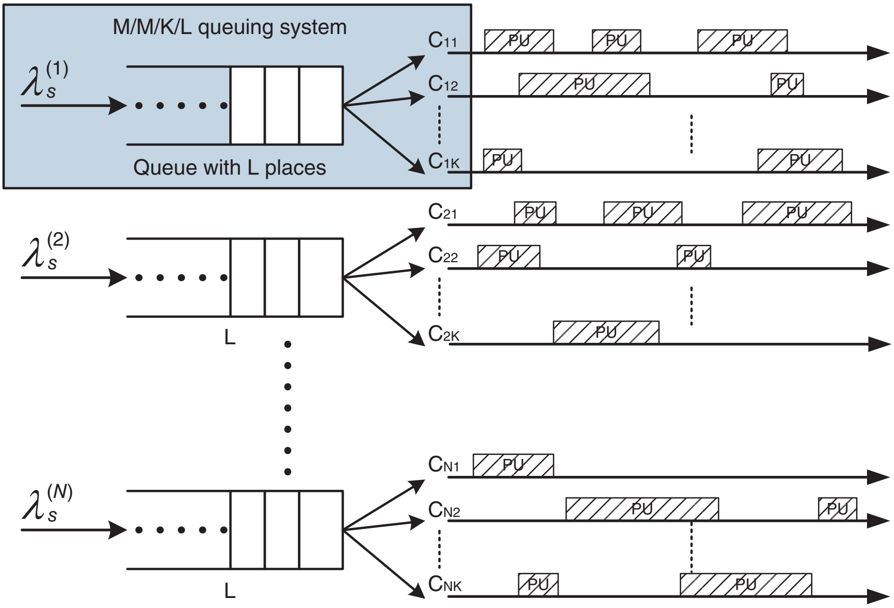

Figure 10.3 Access for SUs modeled as an M/M/K/L queuing system

traffic of the SUs needs to be transmitted in the system, it can be inputted to the queue for the SU connections. This proposed channel selection model could approximate the virtual SU message queue using an M/M/K/L queuing system. If the number of SUs is large, the input traffic of the virtual queue can be modeled as a Poisson process, where K is the number of servers and L is the finite number of waiting positions for each queue.

Let $\lambda_s^{(i)}$ denote the average number of the SUs per unit time in ith concentric ring of radii R_i and L denote the number of unit time as a kind of queue length. Therefore, each queue of this system, namely each ring, can accommodate $\lambda_s^{(i)}L$ number of the SUs. Given the set of candidate channels $\Omega = \{1, 2, \ldots, K\}$ and the set of concentric rings $\mathfrak{R} = \{1, 2, \ldots, N\}$, we denote C_{ij} to be the capability of the SUs in ring $i \in \mathfrak{R}$ within the channel $j \in \Omega$ and have

$$C_{ij} = \text{IEC}(r_{\text{BS}}) \cdot \frac{B}{K \cdot N} \quad \text{(bit/second)} \tag{10.2}$$

where F is the size of SU message and B represents the bandwidth available at the BS. Let μ_{ij} represent the service rate of SU connections using the frequency channel j in ith ring, we have,

$$\mu_{ij} = \frac{C_{ij}}{F} \tag{10.3}$$

Let ρ_i denote the occupation rate (offered traffic load), we have

$$\rho_i = \frac{\lambda_s^{(i)}}{K \cdot \mu_{ij}} = \frac{F \cdot \lambda_s^{(i)}}{K \cdot C_{ij}} \tag{10.4}$$

Assume that p_m is the probability that there are m SU messages in the system and p_{thres} is the blocked traffic rate threshold; therefore, we have

$$p_m = \begin{cases} \dfrac{\rho_i^m}{m!} \cdot p_0 & m \leq K \\ \dfrac{\rho_i^K}{K!} \left(\dfrac{\rho_i}{K} \right)^{m-K} \cdot p_0 & K < m \leq \lambda_s^{(i)} L + K \end{cases} \tag{10.5}$$

subject to:

$$\sum_{m=0}^{\lambda_s^{(i)} L+K} p_m = 1, \tag{10.6}$$

$$p_{(\lambda_s^{(i)} L+K)} \leq p_{\text{thres}} \tag{10.7}$$

Note that the constraint of (1.7) depicts that the blocking rate of SU connections in the virtual queue should be lower than the predetermined threshold p_{thres}.

10.4.4 Wireless Interface Switch

We assume that alternative wireless networks (Wi-Fi, TVWS) may be available at limited locations or time duration. The challenge is whether a mobile device that needs to transfer N MB of data should search for alternative networks to transmit the file and possibly delay the transmission in order to achieve minimal energy consumption cost.

In the case of multiple alternative interfaces, the system should choose the network with the most expected energy saving. In this work, the primary network is the cellular network and the alternative networks are TVWS and Wi-Fi. If the data size transmitted by TVWS L_{TV} or by Wi-Fi L_{W} is smaller than the entire data size L_{total}, which means the entire data cannot be transmitted within the current cell, the system has to determine whether to delay the transmission to the next wireless hotspot cell. Otherwise, it has to utilize LTE access to download the remaining data portion. Meanwhile, if all of the data could be transmitted within the high-speed access coverage like Wi-Fi and TVWS, it will not consider the handover for the remaining data. We categorize the wireless transmission strategies for mobile applications into several different categories as shown in Figure 10.4.

1. Large size with short delay constraint (YouTube-like applications, 10 seconds delay constraint): (i) in the only-LTE-coverage area, the system will predict whether the mobile user can move into the next hotspot under the delay constrains of the applications. If cannot, the user has to utilize LTE interface to download a proportion of file in order to meet the applications' requirements before moving into next hotspot; (ii) within the Wi-Fi and TVWS coverage area, if all the data cannot be transmitted, the system has to determine whether to delay the transmission to next hotspot or immediately transmit the remaining data via LTE. In order to provide better user experience, the system might have to start the wireless transmission immediately to secure enough downloaded data in local storages for video playback rather than waiting until next high-rate hotspot.

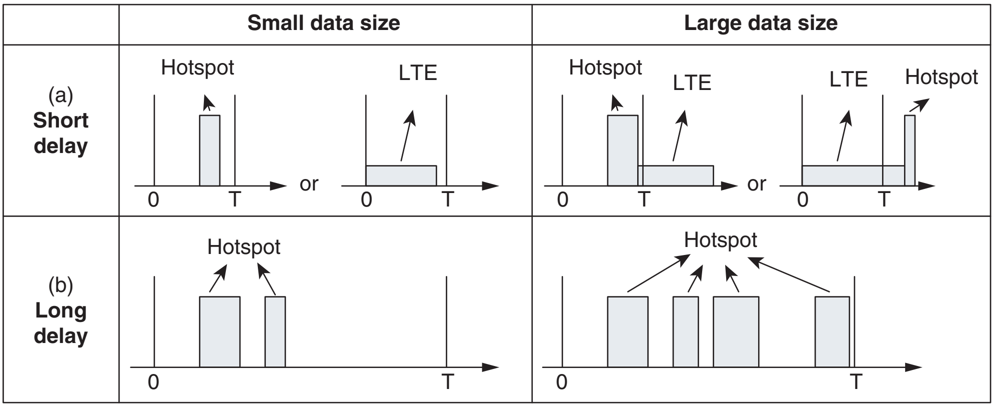

Figure 10.4 Transmission strategy for different data size under delay constraints

2. Small size with short delay constraint (podcast, audio files): the system will launch the file transfer immediately, no matter what kind of wireless radios it could access for transmission.
3. Delay-tolerant applications (e-mail, social network, and APPs updating, 1-minute delay constraint): if the mobile applications are delay-tolerant, the mobile users will have enough time to move into the next wireless hotspot, such as TVWS and Wi-Fi. Therefore, the wireless transmission could be always executed via the high throughput interfaces.

10.5 Numerical Investigations

10.5.1 Trade-Offs between Delay and Cost

In this section, numerical results are presented in general scenarios that a vehicle is moving toward a BS, in which the energy consumption is based on the embedded system of mobile nodes including RF, DRAM, and NAND flash. When the vehicle is approaching closer to the serving BS, then compared to the RF transmission power consumption, power consumption of storage devices will become non-negligible in the prediction of transmission energy consumption as observed from the distinction between Figure 10.5(a) with the distance of 400 meters to the BS and Figure 10.5(b) where the distance is assumed to be 800 meters. Due to the short distance between wireless terminals and the BS, the energy consumption of storage devices will have an increasingly overall effect on the energy cost, which is vividly shown in the curves of Figure 10.5(a).

Moreover, in order to evaluate the importance of time delay for the wireless transmission process, different values of γ are utilized for different applicable situations, such as the file transfer (delay-tolerant), video transmission (delay-sensitive). Figure 10.6 exhibits the difference of energy cost in different values of γ with 5, 10, and 20 second time delay constraints. The hyaline part of the bars stands for the time delay incorporated into the overall energy consumption. $\gamma = 0$ reveals the real value of energy consumption which delay cost has not been comprised. The cases of $\gamma = 1$ and $\gamma = 10$ clearly demonstrate the rising importance of time delay in energy cost.

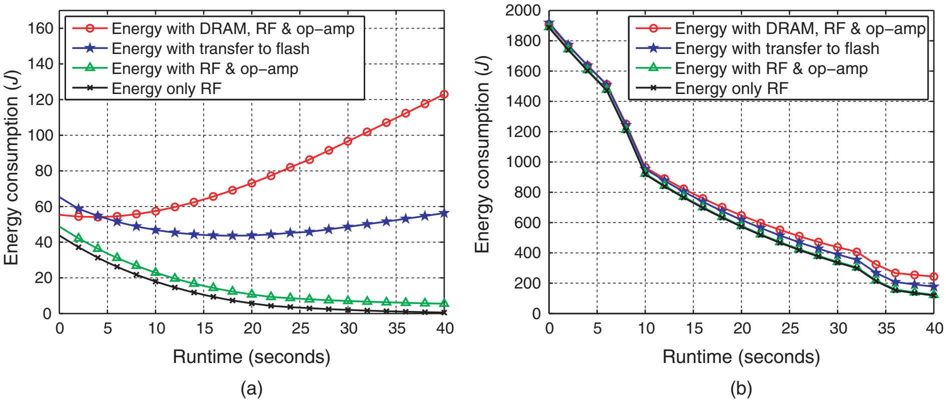

Figure 10.5 Energy cost from different distances to the BS (a) 400 meters to Base Station (b) 800 meters to Base Station

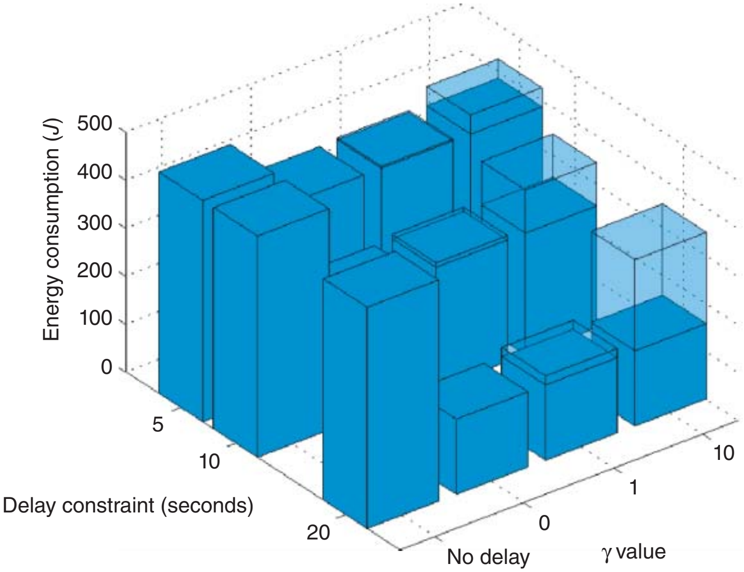

Figure 10.6 Importance of delay constraint in the overall energy cost

10.5.2 Trade-Offs between Transmission and Storage Cost

The research in Ref. [27] tracks the behavior of user requests from a campus network spanning an interval of 10 months. They use a commercial PC with a Data Acquisition and Generation (DAG) card to capture video information from YouTube server.

The values in Table 10.1 from Ref. [27] show the statistics regarding the videos requested during the aforementioned track period. The 4th row (Single) presents the percentage of clips requested by one PC only once, while 5th row (Multi) shows the percentage of videos requested

Table 10.1 YouTube video statistics per digital devices

Trace	Length(h)	Total num	Single(%)	Multi(%)
1	12	12955	77.4	22.6
2	72	23515	77.7	22.3
3	108	17183	77.1	22.9
4	162	82132	72.5	27.5
5	336	303331	65.9	34.1
6	168	131450	68.5	31.5

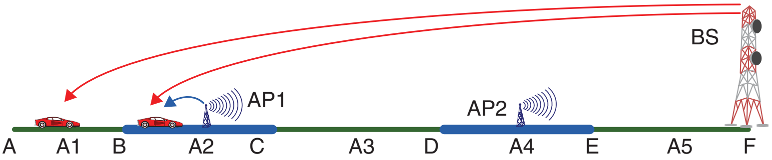

Figure 10.7 The selection from cellular BS and Wi-Fi AP

more than once. These statistics reveal that if the video could be buffered and cached in the local storages of digital devices, it will effectively decrease the wireless downlink traffic and energy consumption at the client end.

It is assumed that the road segment a vehicle is moving along is covered by a cellular BS with two Wi-Fi hotspots (segment BC and DE) in this domain as shown in Figure 10.7. We model the time duration until a popular video is requested again as an exponential distribution with mean time duration μ equal to 60 seconds. Let $\mathcal{A} = \{A_1, A_2, \ldots, A_M\}$ represent the segments along the entire route when the vehicle is moving toward the BS and X denote time interval that the mobile user would potentially re-load the same video. From the cumulative distribution function (CDF), we can calculate the probabilities $\Pr(A_k)$ that the mobile user would make a demand to consume the same content again.

Once a video clip has been downloaded from the multimedia servers and stored in the local DRAM already, there are two possible actions that could be taken. The first is that the content is deleted from the DRAM and hence future requests will have to be streamed again via wireless access. The other option is that the device stores the content in the local DRAM until a hard deadline. Let $E_{\min}(A_k)$ denote the minimized energy cost in area A_k from the storing and streaming schemes, which incorporate energy consumed for wireless transmission in one area, such as electronic circuits in mobile devices, and energy consumed from data transmission. $A_k \in \mathcal{A} = \{A_1, A_2, \ldots, A_M\}$. The strategies strive to balance between storing and transmission in the entire domain and explore the minimized energy cost across a long-term average, which is given as follows:

$$E_{\text{opt}} = \frac{\sum_{k=1}^{M} \{E_{\min}(A_k) \cdot \Pr(A_k)\}}{\sum_{k=1}^{M} \Pr(A_k)} \tag{10.8}$$

The proposed strategies combine transmission and selective storing aiming to achieve long-term energy efficiency according to the time interval distribution of user demand. The

Table 10.2 Probabilities and energy consumptions in different area

Area	Energy for rx (J)	Energy for store (J)	Probability %
A_1	45, 894.0	46.6088	0.2835
A_2	1509.8	151.4587	0.3408
A_3	2812.0	279.6088	0.3935
A_4	64.2	407.7587	0.3408
A_5	106.8	524.2587	0.3408

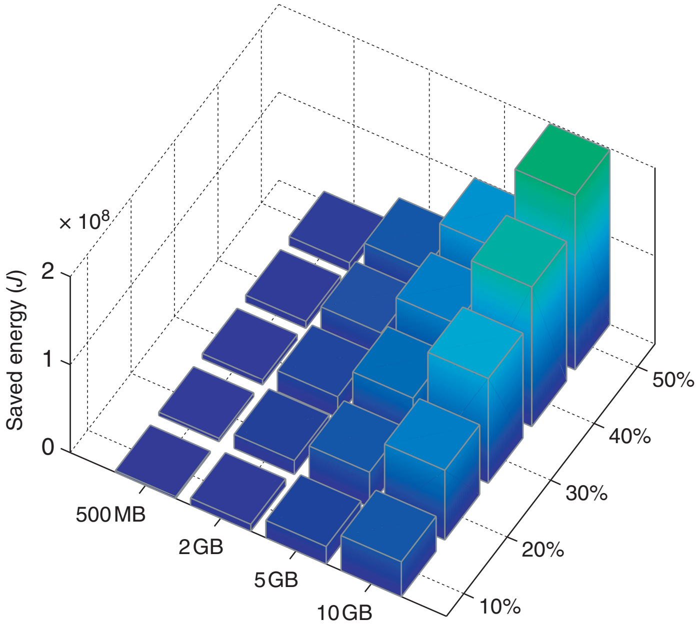

Figure 10.8 Saved energy consumption of the proposed over one month compared to the always streaming scheme

figures in Table 10.2 suggest that in the area A_1, A_2, and A_3, the device should store the downloaded content in local DRAM in case the mobile user would request this content again in a short time period. Although in the area A_2 with Wi-Fi coverage, the majority of transmission energy is less than the energy to store it in the local DRAM, the energy consumption of storing the content in the local DRAM performs better than the scheme that always downloads via wireless access on a long-term average.

Figure 10.8 depicts the energy saving for an individual mobile user in one month, compared with the always streaming scheme with different elastic percentage and cumulative content size. These results suggest that as mobile users frequently request the same video content, our proposed scheme could save a considerable portion of energy consumption, thus prolonging the lifetime of digital devices.

Table 10.3 Simulation results ($p_{\text{thres}} = 0.10$)

Num of ring	Num of time unit	Max length	Packet length F (Mbits)	Blocking probability
1	42	7	1	0.0490
2	23	11	1	0.0909
3	84	14	1	0.0477
4	77	22	1	0.0909
5	167	29	1	0.0805
6	188	33	1	0.0909
Total	581	116	1	N/A
Optimal	188	199	1	0.0955

10.5.3 Maximum of SU

The SUs must firstly monitor all frequency channels to sense the arrival of PU connections. The SU virtual queue senses the frequency channel in an increasing order, from 1th to the Mth channel. When finishing sensing channels and finding the available candidate channels, SUs regard PU traffic load as stable within a short time duration. Then, queuing system modeling can be utilized to analyze the competition of SU connections without consideration of PU connections.

Table 10.3 presents the simulation parameters and results with a blocking traffic threshold $p_{\text{thres}} = 0.10$ for the SU queue. It can be clearly seen from the results that when the mobile nodes are moving toward the service BS, the length of time units in each ring becomes less owing to the increasing capability of rings in terms of transmission rate. Moreover, with the decreasing distance between wireless nodes and the BS, the ring could accommodate a larger number of SU messages, that is, the SU virtual queue could accommodate a larger number of the SUs simultaneously.

In this model, we assume that there are two situations for a comparison in order to show the benefit of energy consumption: (i) the bandwidth of the service BS is divided into six equal parts, and each ring could only use one part for transmission; (ii) the bandwidth is occupied exclusively by the last ring, which is closest to the service BS. For instance, in the 7th line of Table 10.3, the SUs buffer all the messages and move into the area of the ring that is closest to the service BS. In this case, the SUs in the last ring occupy all of the bandwidth for message transmission, so that the capacity and throughput will be the maximum possible because this ring can support the higher constellation.

10.5.4 Battery Lifetime

It is assumed that the road segment a vehicle is moving along is covered by a cellular BS with two TVWS hotspots and two Wi-Fi hotspots in this domain as shown in Figure 10.9. Let $\Gamma = \{\tau_i, \tau_{i+1}, \ldots, \tau_j\}$ denote the decomposed time slots in which mobile users are moving along a

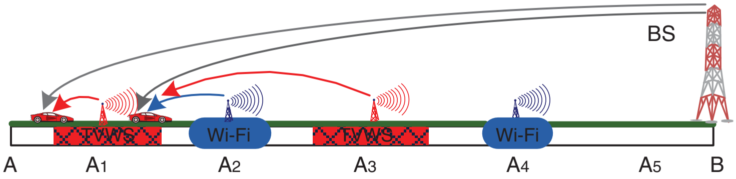

Figure 10.9 The selection from cellular BS, Wi-Fi, and TVWS AP

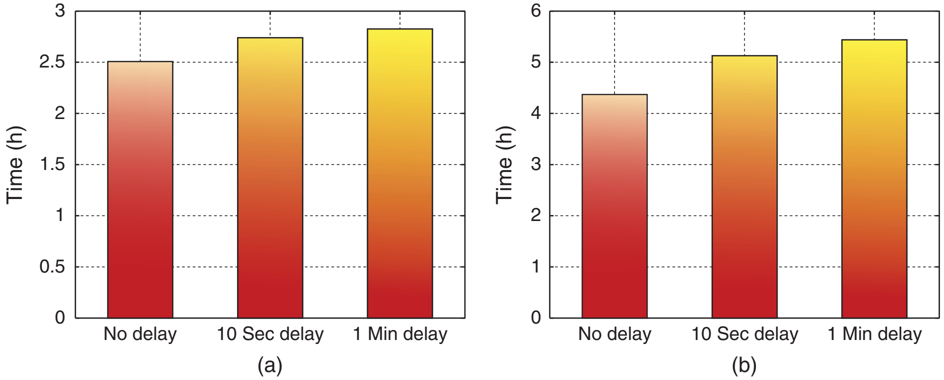

Figure 10.10 Battery life for different mobile applications (a) Video play back (b) Audio play back

road. Let $Q(t) = \{q_i, q_{i+1}, \dots, q_j\}$ represent the energy consumed from embedded peripherals, such as CPU, Graphics, backlight, and storage devices.

Previous statistics have shown that the average multimedia video size is 10 Mb on YouTube, which is a nominal value for such video files [28]. Hence, we assume that the average length of a YouTube video is 4 minutes and 12 seconds, so in one cell, the mobile user will watch 250 seconds video, which translates to about 100 Mb downloading from wireless radios on average. Additionally, it is assumed that the mobile devices have a lithium-ion battery with a capacity of 1200 mAh, 3.7 V. Figure 10.10 shows a comparison of the battery lifetime of two mobile applications (video playback and audio playback) in three different scenarios. In the first scenario, when the mobile users make a request for the application, the system will start wireless transmission immediately without any delay. In the second and last scenarios, the mobile systems would delay the wireless transmission by 10 seconds and 1 minute, respectively. In the case of video playback, as seen in Figure 10.10a, the strategies that allow delay for mobile application can achieve drastic energy savings. As a result, the 10 second delay constraint strategy and 1 minute delay constraint could extend the battery lifetime by 9.3% and 12.7%, respectively.

As can be seen in Figure 10.10b, the proposed schemes, which allow delays on the transmission, perform better than the non-delay schemes due to the fact that in the audio playback scenario, the embedded system will have less CPU utilization with the backlight off, which takes a significant portion of overall energy consumption in the video playback scenario.

10.6 Conclusions and Future Research

The energy-delay trade-off has emerged as a key concern aspect in wireless communications. In this context, this chapter explores a set of novel transmission schedules in cognitive radio enabled networks for highly elastic messages aiming to select best time interval for message transmission in order to achieve significant energy efficiency under delay constraints. The proposed techniques take also into account the energy consumption of embedded storage memory at the terminal, which is used as a cost when message transmissions are delayed. Furthermore, when wireless nodes are competing for secondary access to the medium, the estimation of probability of PU arrival rate and service time is important for vehicular wireless device (SU) to effectively occupy the primary spectrum. The mobile nodes firstly contact a trusted database for historical information about PU traffic at a specific location and time duration so as to estimate the probability of the SU connections. Then, regarding the SU traffic, it is shown that it can be modeled as an M/M/K/L queuing system, which allows to analyze the capability that the system can serve users simultaneously. In this case, for the delay-tolerant applications, we recommend to delay the message transmission to the area close to the BS and maximize the throughput potential to minimize the energy consumption of message transmission under several constraints. In addition, for popular video streaming applications on portable devices that could be watched many times by one user, we studied the trade-offs between storing video content locally at the DRAM of the device or allowing deletion of the content from the local memory and relaying in wireless streaming in near-future requests of the same content. To this end, a scheme has been proposed where the mobility of the user is taken into account together with the probability of a user requesting the same content multiple times so that a decision is taken of whether or not the content should be stored locally. Finally, we analyze the problem of how to prolong the battery lifetime of mobile devices. This is especially important since the proliferation of always-on Internet applications has put significant strain on the battery capabilities and shortening the required re-charging time periods of the devices. Previous research has revealed that the data downloading via wireless radios is a dominant energy consumption factor in mobile devices. To avoid the drain of mobile device batteries, based on the delay tolerance of mobile Internet applications, we design the strategies that making selective use of the available high-rate wireless access such as roadside Wi-Fi/TVWS APs, by considering the energy cost, RF coverage, capabilities, and transmission algorithm.

In all of the aforementioned techniques in this chapter, the salient assumption was that energy savings can be achieved by capitalizing on the elasticity of Internet applications. This is an emerging area of research with significant potential to provide solutions for sustainability and better utilization of scarce wireless resources. Future avenues of research within this domain need to encompass a more architectural view on the wireless access network including overall system-required functionalities in order to allow for such mechanisms to be implemented in emerging and future wireless/cellular networks.

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