SERO: A Model-driven Seamless Roaming Framework for Wireless Mesh Network with Multipath TCP

Abstract—**While modern wireless devices are capable of using multiple WiFi interfaces, the Multipath TCP (MPTCP) protocol has been employed to make full use of the capacity of many radios by enabling multiple path communication simultaneously. To provide exceptional mobility support in wireless networks, a key question is to determine the best handoff strategy to switch between access points (APs) or among WiFi/3G interfaces during roaming. In this paper, we propose SERO, a novel model-driven SEamless ROaming framework to optimize layer-2 handoff and vertical handoff for multihomed devices using MPTCP. The proposed framework adopts a measurement-based method to derive the TCP throughput model for wireless communication with or without handoff. Based on the throughput model, we propose a hybrid handoff strategy that uses multiple WiFi interfaces for data transmission and employs 3G augmentation to bridge the network interruption caused by handoff and to guarantee the total throughput above a predefined threshold for roaming devices. We implement the SERO framework in a real-deployed wireless mesh network testbed, and evaluate its performance by extensive experiments, which shows that SERO achieves performance gain of 26%-180% compared to several existing handoff strategies.**

I. Introduction

The recent years have witnessed a quick development of wireless local area network (WLAN) techniques, which show two trends in providing wireless Internet service. On one hand, small cells such as WiFi access points (APs) and femtocells are densely deployed at workplace and home, which enable the end user to choose the best AP to access the Internet. Wireless mesh network (WMN) is such a technology that organizes wireless routers in a mesh topology using ad hoc mode to form a wireless communication backbone, which employs distributed multi-hop routing protocol to connect the wired infrastructure and provides Internet access to wireless devices via densely deployed mesh APs. On the other hand, mobile clients such as laptop and cellphones are multihomed, which are typically equipped with multiple radios including WiFi, 3G and Bluetooth. They are also extendable to use multiple WiFi interfaces via USB ports. In order to make full use of the capacity of the radios, the Multipath TCP (MPTCP) protocol [1], [2] was introduced by the IETF to extend traditional TCP to achieve multiple path communication over many radios simultaneously. MPTCP creates several TCP subflows for a single application, each of which may take a different path through the network to achieve maximum bandwidth usage and robustness.

Mobility is the most important issue to be addressed in wireless networks. When a mobile client moves away from an access point, it may disconnect from the current AP and switch to a new one nearby. The change of AP association is known as handoff, which will cause interruption in network connectivity.

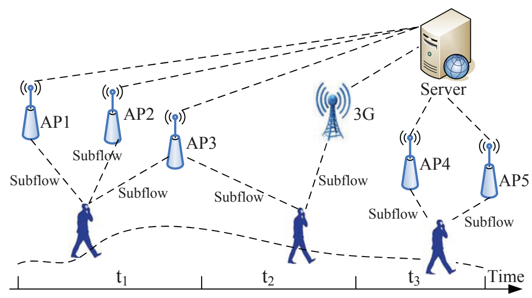

Fig. 1. Scenario of seamless roaming with multiple interfaces.

To support seamless roaming for mobile device, a fast handoff mechanism that is transparent to higher-level communication protocols is highly desirable. In the current 802.11 WLANs, wireless interface tends to associate with AP having the strongest signal strength indicated by the Received Signal Strength Indicator (RSSI), and performs handoff only when the RSSI value drops below a threshold, which may lead to poor performance [3]. Layer-2 handoff are widely used by mobile devices to switch between APs while maintaining transparent to the upper level protocols, which may cause network delay as long as several seconds [4], [5], [6]. Layer-3 handoff uses IP-in-IP tunnel to enable routing to a roaming domain without changing IP address [7], [8]. Handoff mechanisms using multihoming technology have been proposed in [9], [10], [11], [12], most of which require special modification of AP hardware drivers in order to transfer connectivity from one access point to the next. Different from the existing works, we focus on seamless roaming of multihomed devices exploiting both layer-2 handoff (switching from AP to AP) and vertical handoff (switching between WiFi and Cellular connections) to maintain active network connectivity and achieve maximum throughput with Multipath TCP protocol.

A. Motivation example

We use the scenario in Fig. 1 to show the benefit of a hybrid handoff mechanism for a multihomed device. In duration t_1 in the figure, a user associates his device to AP_1, AP_2 and AP_3 to establish multiple subflows using MPTCP for download. When the user moves further, he loses the connection to AP_1 and AP_2 in t_2. Due to the scarcity of APs in range, the 3G interface of the mobile device is activated to establish subflows in order to maintain MPTCP connectivity and to guarantee download throughput. When the user enters the coverage area of AP_4 and AP_5 in t_3, he switches back to WiFi to keep multipath downloading and turns off 3G to save cost. In this example, layer-2 handoff occurs in t_1; vertical handoff occurs in t_2; and both layer-2 and vertical handoff occur in t_3.

The multipath TCP had been supported by the Apple iOS 7 to enhance the service of interactive applications such as Siri, which maintains long-term network connection via multiple interfaces and allows switching traffic from one connection to another without interruption. Towards the trend of Wi-Fi and cellular integration, hybrid handoff optimization has drawn much attention from both academic and industry.

B. Overview of the framework

The existing handoff strategies have several drawbacks: they may need modification of hardware, may interrupt all ongoing TCP flows, or can not adapt to the change of network workload. MPTCP enables seamlessly switching between network connections without modification of hardware and applications, which can be applied to overcome the above drawbacks.

We propose SERO, a **SE**amless **RO**aming framework for WMN with multipath TCP. The main idea is to provide measurement-based and model-driven handoff decision using MPTCP. The measurement-based solution can cope with the dynamics of wireless network characteristics due to mobility, and the model-driven strategy allows using empirical model to estimate future performance, which helps to optimize handoff decision to satisfy various objectives such as maximizing network download throughput, minimizing 3G usage, and reducing handoff latency and frequency, etc.

The SERO framework is shown in Fig. 2. The main steps are described as follows. At the beginning, measurements of TCP throughput and wireless network parameters are made for different scenarios. Based on the measured data, three models are constructed: the *propagation model* which predicts the change of RSSI due to movement; the *throughput model without handoff* which estimates the download throughput based on measuring RSSI and the number of nearby users; and the *throughput model during handoff* which describes the interruption and recovery of network service in layer-2 handoff process. Furthermore, the derived models are used for AP selection and handoff decision in WMN by solving a handoff optimization problem to enhance WiFi throughput and to reduce 3G usage. Finally, the SERO framework is implemented in a real-deployed testbed for performance evaluation and comparison.

C. Contribution

Our main contributions are summarized as follows:

- **Measurement-based TCP throughput models in WMNs.** We measure the TCP throughput for different scenarios in the WMN testbed, and construct the models for throughput estimation of mobile devices. Specifically, we use the propagation model to predict the change of RSSI; we apply the Logistic function to depict the throughput during layer-2 handoff; and we derive a Shannon-like equation for throughput estimation based on the measurement of RSSI and number of users.

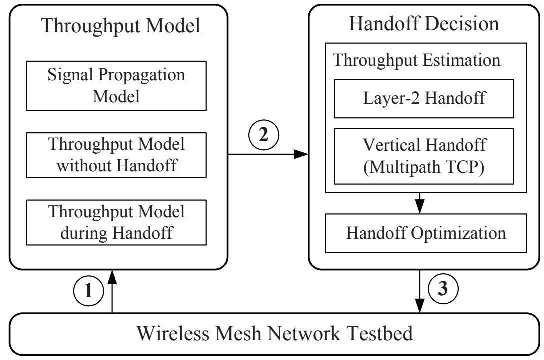

Fig. 2. Overview of the seamless roaming (SERO) framework: ① Constructing throughput models based on a real deployed WMN testbed; ② Applying the throughput models to optimize handoff decision; ③ Implementing the optimal handoff strategy in the WMN testbed for performance evaluation.

- **A model-driven strategy to optimize hybrid handoff decision in WMN with multipath TCP.** Based on the estimated throughput, we introduce a hybrid handoff strategy exploiting layer-2 handoff and vertical handoff of multi-homed device to achieve seamless roaming in WMN. We show that the handoff decision problem with MPTCP can be formulated as an optimization problem, which can be solved by Integer Programming.
- **Implementation and performance evaluation based on real-deployed WMN testbed.** We implement the proposed optimal handoff strategy in a WMN testbed deployed in office environment, and compare it with several heuristic strategies. Experiment results show that the SERO framework achieves the performance gain as high as 26%-180%, and 3G usage as low as 5%-81% compared to the other strategies.

II. Related Work

Seamless roaming in wireless mesh networks allows mobile devices moving from the coverage area of one AP to another without interrupting network service, which concerns several technologies including fast handoff [4], [5], [6] and AP association [13], [14], [15].

Layer-2 handoff occurs when a mobile device moves away from the radio range of one AP and reconnects to another, maintaining the IP address unchanged and transparent to the upper level. Efforts have been made to minimize the handoff latency of mobile users so as to provide seamless connectivity. SyncScan [4] proposed a fast handoff mechanism by tracking nearby base stations and synchronizing the listening periods of mobile clients with transmission periods of APs. Mishra et al. [5] and M. Shiin et al. [16] utilized the topology of the deployed APs to reduce handoff latency and used neighbor graph techniques to update the network topology information by continuously monitoring the nearby APs. Several works studied the handoff minimization problem, intending to minimize the handoff frequency during roaming [6].

Layer-3 handoff has been well studied in mobile Internet to offer transparent mobility support to applications [17]. Mobile

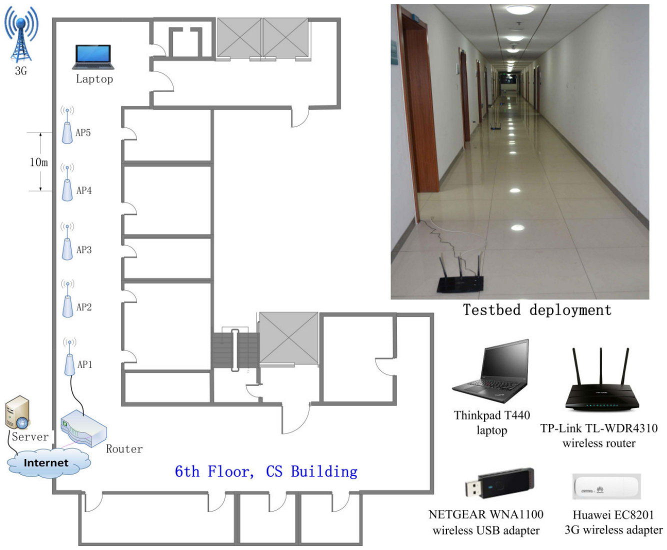

Fig. 3. Deployment of a wireless mesh network testbed.

IP (MIP) [7], [8] was the most well-known network-layer mobility solution, where IP-in-IP tunnel was used to enable routing to a roaming domain without changing IP address.

The multihoming technology makes use of multiple network interfaces or IP addresses on a single mobile device, which enables vertical handoff, where user can switch from one interface to another to avoid interface link failure and enhance network connectivity [18]. In recent years, multipath TCP (MPTCP) was proposed to extend traditional TCP to cope with multiple path communication using multiple radios to achieve maximum bandwidth and robustness [1], [2]. MPTCP enables an application-level handoff that applications can use multiple wireless interfaces simultaneously or alternatively [12].

In recent years, several works addressed the issues of AP selection in multi-hop wireless mesh networks (WMNs) [14], [15]. Cui et al. [14] took load-balancing, multihop characteristics and signal strength into consideration, and proposed an AP association approach to improve network throughput and Max-Min user fairness. A cross-layer framework for association control in WMNs was proposed in [15], where an airtime-metric based on the channel quality and communication loads was introduced for hybrid association control. However, all the above mentioned work do not consider the possible multi-path transmission such as MPTCP in wireless mesh networks.

Different from the existing works, we concern handoff decision issues in the context of multi-path TCP transmission with multihomed devices in wireless mesh networks, and propose a model-driven framework to take hybrid handoffs into account to achieve seamless roaming in WMNs.

III. Wireless Mesh Network Testbed

We set up a wireless mesh network testbed with wireless routers deployed in indoor office environment. Fig. 3 shows the topology of our testbed, where five APs (TP-LINK TL-WDR4310 wireless routers) are deployed in the hallway of the sixth floor, building of the department of computer science in our university. The APs are numbered by $AP_1, AP_2, \cdots, AP_5$ accordingly. The distance between two APs is about ten meters. The 1st AP is connected to the local area network (LAN), while the others can reach AP_1 via multi-hop wireless links. The ith AP uses the $(i-1)$th AP as gateway, forming a multihop wireless mesh network. Each AP is capable of operating on both 2.4GHz frequency and 5GHz frequency. We employ 2.4GHz frequency (channel 11) for device-to-AP communication using AP mode, and 5GHz frequency (channel 36) for AP-to-AP communication using ad hoc mode. Each AP installs the OpenWrt (https://openwrt.org/) firmware (barrier breaker 14.07) and runs the B.A.T.M.A.N. mesh routing protocol (http://www.open-mesh.org/projects/open-mesh/wiki) to enable multi-hop wireless communication.

The mobile clients are several smart phones and laptops. The major measurement is conducted on three laptops (Thinkpad T440, Thinkpad X200s, and ASUS N56XI323VZ-SL). Each laptop has build-in wireless network adapter, and is equipped with a Netgear WNA1100 b/g/n USB wireless network adapter, and a Huawei EC8201 3G wireless adapter. A PC server running Apache httpd 2.4.12 is deployed at the edge of network, which can be accessed using HTTP protocols.

We installed MPTCP protocol in both the server and client sides to enable multipath transmission. The MPTCP is configured to the "full-mesh" mode on the client side: when it downloads files from the server, each active wireless adapter will establish an MPTCP subflow to the server in order to facilitate transmission via multiple paths.

We conduct experiments in the testbed to measure throughput variations with and without handoff operation. In the experiments, several students hold mobile devices to walk through the hallway for several rounds using a web browser to download a large file from the HTTP server. During movement, the WiFi interfaces of the mobile device are associated to nearby APs according to some association strategy (e.g., associating to the most proximate AP). To test the network performance during handoff, the AP association of each interface-AP pair changes every 10 seconds. We record the download throughput and the RSSI values during walking. Specifically, we use TCPdump (http://www.tcpdump.org/) to capture communication packets from the wireless interfaces, and record the beacon frames and TCP segments to a log file for analysis. The beacon frames contain the RSSI values with timestamps, which are transmitted periodically by each AP to announce the presence of a wireless LAN with typical frequency of 10 beacons per second in the 802.11 protocol. The TCP segments contain payload information with timestamps, which can be used to calculate instantaneous download throughput accurately.

IV. Throughput Models in WMNs

This section introduces three models in WMNs: a propagation model, a throughput model without handoff, and a throughput model during handoff, which correspond to the left part of Fig. 2 of the framework.

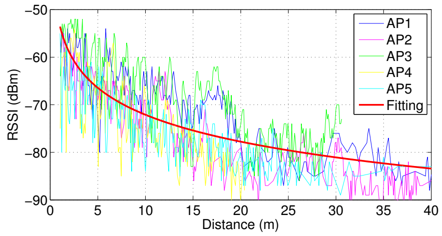

Fig. 4. RSSI vs. distance ($r_0 = -53.31$, $\alpha = -1.88$, $d_0 = 1$).

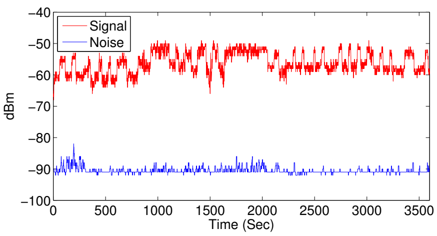

Fig. 5. Signal strength and noise level.

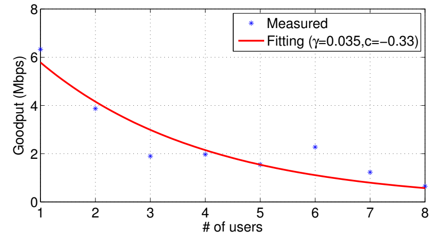

Fig. 6. Throughput vs. the number of users.

A. Propagation model for RSSI estimation

We explore the model of received signal strength (i.e., RSSI) variation for mobile devices. We focus on the following question: given the measurement of RSSI in the past, how to estimate the changing of RSSI value in the next time slot during roaming.

According to the study of [19], [20], RSSI is a function of the distance between the transmitter and receiver, which can be expressed by the well-known propagation model:

$$RSSI[dBm] = \phi(d) = r_0 + 10\alpha log_{10}(d/d_0), \qquad (1)$$

where d is the distance of the AP to wireless interface; d_0 is a reference distance with typical value of one meter; r_0 is the signal power at distance d_0; and α is the path loss component that indicates the rate at which the path loss increases with distance. Generally, r_0 can be either derived empirically or obtained from the wireless hardware vendor, and α can be derived empirically.

We test the theory by fitting the function $\phi(d)$ with the measured data in our experiments. Fig. 4 shows how RSSI varies with distance d for the five APs. According to the figure, the RSSIs of the APs fit the propagation model $RSSI = -53.31 - 18.8log_{10}(d)$ very well.

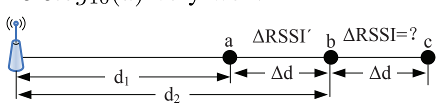

Fig. 7. $\Delta RSSI$ estimation.

We now focus on the estimation of RSSI variation due to mobility as illustrated in Fig. 7. Assuming time is slotted, when a mobile device moves from location b to c in a time slot, what is the change of received signal strength $\Delta RSSI$? If the distances to the AP, d_1 and d_2, are known, $\Delta RSSI$ can be easily obtained by using equation (1). However, in the real deployment, the distance from a mobile device to the AP is not easy to measure, thus $\Delta RSSI$ can not be calculated from equation (1) directly.

We derive a solution as follows. Since the RSSI in the previous time slot can be measured, we show that $\Delta RSSI$ can be derived from the measured $\Delta RSSI'$ in the previous time lot.

When time slot is sufficiently small, the moving distance Δd is small, and it is approximately the same in consecutive time slots. Taking the derivative of equation (1), we have

$$\phi'(d) = \frac{10\alpha}{ln10}\frac{1}{d} = 4.34\alpha\frac{1}{d}. \qquad (2)$$

For small Δd, it satisfies

$$\Delta\phi = 4.34\alpha\frac{1}{d}\Delta d. \qquad (3)$$

Thus $\Delta RSSI' = 4.34\alpha\frac{1}{d_1}\Delta d$. Therefore

$$\begin{aligned}\Delta RSSI &= 4.34\alpha\frac{1}{d_2}\Delta d = 4.34\alpha\frac{1}{d_1+\Delta d}\Delta d \\ &= 4.34\alpha\frac{1}{d_1/\Delta d + 1} \\ &= \frac{\Delta RSSI'}{1+\Delta RSSI'/(4.34\alpha)}. \qquad (4)\end{aligned}$$

Thus if $\Delta RSSI'$ is measured in the previous time slot, $\Delta RSSI$ in the next time slot during roaming can be estimated by equation (4).

B. Throughput model without handoff

We then study how TCP throughput is influenced by RSSI. Generally speaking, when a wireless device is in motion, its throughput will increases/decreases when RSSI becomes stronger/weaker.

In information theory, Shannon's Theorem [21] gave an upper bound of link capacity by using a logarithm function of signal-to-noise ratio:

$$Capacity = Blog_2(1+\frac{S}{N}), \qquad (5)$$

where B is the bandwidth of the channel; S is the average received signal power over the bandwidth; and N is the average noise or interference power over the bandwidth.

Inspired by the Shannon's equation, we can roughly consider TCP throughput as a proportion of the theoretical upper bound capacity, which can be expressed by the following Shannon-like equation:

$$Throughput[Mbps] = wBlog_2(1+10^{\frac{RSSI-b}{10}}). \qquad (6)$$

The parameters of the above equation are explained as follows. (I) B is the bandwidth of the channel (MHz). For 802.11b/g/n protocols in our wireless mesh network testbed, $B = 20MHz$. (II) b is the background noise. When both $RSSI$ and b take dBm as the unit of measure, $RSSI - b$ equals to signal-to-noise ratio in dB, and S/N equals to $10^{\frac{RSSI-b}{10}}$ [22]. (III) w indicates the proportion that the effective TCP throughput achieved by the WiFi interface to the theoretical upper bound capacity.

In the general wireless communication situation, $10^{\frac{RSSI-b}{10}} \gg 1$, so equation (6) can be simplified as:

$$Throughput[Mbps] = \frac{log_2 10}{10} w B(RSSI - b). \quad (7)$$

In the real-deployed wireless mesh network, we made the following observations to the above equation.

Observation 1: The background noise is a near constant. According to [22], the most common background noise in wireless communication is Gaussian White Noise, which fluctuates slowly around an average value. In our wireless mesh testbed, we measure the background noise using Apple's WiFi Diagnostics tool to collect data for one hour. The results are shown in Fig. 5. According to the figure, the received signal strength fluctuates dynamically between -70 to -50 dBm. The background noise level is a near constant, which varies slightly around the value of -90 dBm in our measurement.

Observation 2: The effective TCP throughput decreases exponentially when the number of users increases. Intuitively, TCP throughput is not only affected by the received signal strength, but also affected by the number of hosts contending for communication channel. Thus the parameter w in equation (7) should be a function of m, where m is the number of users transmitting data with the same AP.

We conduct experiments in our testbed to test the impact of contention. The blue dots in Fig. 6 indicate the average TCP throughput when the number of users m varies from 1 to 8. It is observed that the average throughput decreases exponentially when m increases. The reason is that when there are more than one user communicating with the same AP, there will be collision in data transmission. The 802.11 protocols employs CSMA/CA mechanism [22] for media access control, and make binary exponential backoff to avoid collision, which yields an exponential decrease in throughput.

According to the observation, w is an exponential function of m with the form $w(m) = \gamma e^{c \cdot m}$. Substituting $w(m)$ to equation (7), the TCP throughput can be modeled as:

$$Throughput[Mbps] = \frac{log_2 10}{10} \gamma e^{c \cdot m} B(RSSI - b). \quad (8)$$

We use the nonlinear least-squares curve fitting in Matlab to fit this equation with the observed data. The fitting result is show in the red-line in Fig. 6. It can be seen that the fitting curve approaches the mean of average measured throughput closely for parameter $\gamma = 0.035,\ c = -0.33$.

C. Throughput model for layer-2 handoff

We study the layer-2 handoff process in wireless mesh networks. During layer-2 handoff, a WiFi interface takes the following actions including disconnecting from the current AP passively or actively, detecting nearby APs by listening to the beacon frames, and reconnecting to a new AP without changing the IP address. The handoff process will cause longer communication delay and degradation of network performance due to the cost of channel scanning, authenticating and reconnecting to a new AP. In this section, we model how throughput is influenced by layer-2 handoff in WMN.

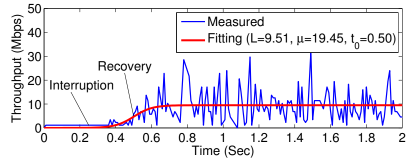

Fig. 8. TCP throughput of an AP in handoff.

Fig. 8 shows the instantaneous throughput of an AP in the handoff duration from disconnecting the current AP to resuming the network service. As shown in the figure, the handoff process consists of two stages: the *interruption stage* and the *recovery stage*.

In the interruption stage, the throughput drops to zero, due to wireless interface disconnections. In the recovery stage, the throughput increases from 0 to a high value. Due to rate adaption in WiFi and flow control in TCP, the recovery stage lasts for a duration within which the throughput increases quickly. After recovery stage, the throughput will remain a relative stable level.

The change of throughput during handoff looks like a S-shaped curve, which inspires us to model it using a Logistic regression model [23]:

$$Throughput[Mbps] = \zeta(t) = \frac{L}{1 + e^{-\mu(t - t_0)}}, \quad (9)$$

where t_0 is the x-value of the sigmoid's midpoint; μ represents the steepness of the curve; and L is the expected throughput after recovery.

We use Logistic regression to fit the equation with the observed data. The results are shown in the readline in Fig. 8, which seemly fits the average bandwidth during handoff.

D. Towards online measurement and implementation

To apply the proposed models in the real-deployed WMN testbed, there are several implementation issues.

The propagation model for RSSI is easy to be applied in practice. Since the WiFi interface can receive beacon frames from all APs which report RSSI every 100 milliseconds, the RSSI values in the past can be used to estimate the RSSI changes in the next time slot by using equation (1).

To estimate the throughput of mobile devices, several arguments should be determined. In equation (8), B is the channel bandwidth which is 20MHz in our testbed. Background noise b is a near constant ($-90\ dBm$) according to our measurement. The argument γ and c indicate how quick the throughput drops when the number of user increases, which can be derived ahead of time empirically. RSSI can be obtained in realtime by listening to beacon frames. The number of users m can also be obtained in realtime by either sending a query to the AP or by listening the RTS/CTS frames [22] sent by the nearby wireless devices.

Since throughput during handoff is quite diverse, we can roughly estimate it using equation (9). The arguments t_0 and μ can be derived by their average value empirically (which is $t_0 = 0.7$ and $\mu = 85$ in our experiments). The argument L represents the throughput after handoff, which can be estimated in realtime using equation (8).

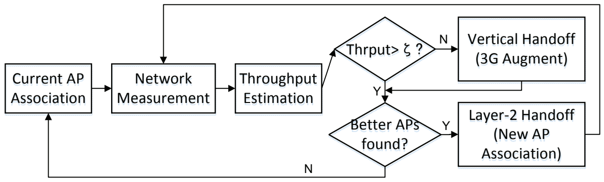

Fig. 9. Flowchart of the hybrid handoff strategy.

With the derived arguments, it is possible to develop an online algorithm to determine the optimal handoff strategy, which is presented in the following section.

V. Optimizing handoff decision

This section derives the optimal handoff strategy corresponding to the right part in Fig. 2 of the framework.

A. Assumptions and notations

Throughout this paper, the following and notations are used.

- There are n APs in the wireless mesh network, which are denoted by the set $\mathcal{A} = \{AP_1, AP_2, \cdots, AP_n\}$.
- A multihomed wireless device is equipped with k WiFi interfaces, which are denoted by the set $\mathcal{W} = \{W_1, W_2, \cdots, W_k\}$; it is also equipped with a 3G interface, which is indicated by $\hat{W}$.
- Assume time is slotted and divided into several periods. The length of each period (e.g., 10 seconds) is T. Handoff decision is made at the beginning of each period.
- The throughput of each wireless interface is measured by a monitoring program periodically. The average throughput between W_i and AP_j is denoted by g_{ij}.
- Assume $\hat{g}$ is the throughput of the 3G interface. Since 3G technology enables wide-area wireless coverage, $\hat{g}$ can be regarded as a constant for indoor movement.

B. Throughput estimation

Given the measured $RSSI$ and the number of nearby users m in the previous period, the throughput g_{ij} when WiFi interface W_i is associated to AP_j in the next period can be estimated using the proposed throughput models.

According to equation (4), there is a change of signal strength $\Delta RSSI$ in the next period. Applying equation (8), g_{ij} can be calculated by

$$g_{ij} = \frac{log_2 10}{10} \gamma e^{c \cdot m} B(RSSI + \Delta RSSI - b). \tag{10}$$

C. Average throughput during layer-2 handoff

Equation (10) gives the estimated throughput without considering handoff. When a mobile device performs layer-2 handoff, equation (9) depicts its instantaneous throughput. Assume T' is the duration of the handoff process, the average throughput during handoff can be calculated by

$$\frac{1}{T'} \int_0^{T'} \frac{g_{ij}}{1 + e^{-\mu(t-t_0)}} dt. \tag{11}$$

Here T' can be derived empirically. According to our experiments in section IV-C, the average length of interruption stage and recovery stage are 0.6 second and 0.2 second accordingly. Thus $T' \approx 0.6 + 0.2 = 0.8$ second in the testbed.

D. Handoff strategy

In the proposed SERO framework, we adopt a hybrid handoff strategy using MPTCP. Since MPTCP allows WiFi and 3G being used simultaneously or alternatively, we can use WiFi for most data transmission and exploit 3G augment to achieve guaranteed throughput during roaming.

The main idea is explained in Fig. 9. Starting from current AP association, the mobile device periodically performs network measurement and throughput estimation using the proposed model. During movement, if it detects a degradation of throughput below a predefined threshold ξ (typically be a value smaller than the minimum bandwidth of 3G and WiFi), 3G interface is activated to create subflow, which triggers the vertical handoff that offloads WiFi traffic to 3G interface without interrupting TCP connectivity. If it discovers better APs nearby, the layer-2 handoff will be triggered and it will associate to a new set of APs. From the application's point of view, the handoff process is transparent and its TCP throughput is smooth during roaming. The optimal strategy for hybrid handoff with 3G augmentation is discussed below.

E. Problem formulation and solution

On one hand, we target at maximizing the WiFi throughput exploiting multipath transmission while reducing the delay and cost caused by handoff; on the other hand, we would like to provide the guarantee of a minimum throughput threshold ξ for TCP download. In the worse case, there is no AP in range and only 3G is available for download.

We introduce indicators x_{ij}, $x'_{ij} \in \{0, 1\}$ $(i = 1, \cdots, k; j = 1, \cdots, n)$ to denote AP association in consecutive periods.

$$x_{ij}\ (or\ x'_{ij}) = \begin{cases} 1 & if\ W_i\ is\ associated\ to\ AP_j \\ 0 & otherwise. \end{cases} \tag{12}$$

We assume that x'_{ij} indicates the AP association in the previous period which are known. And x_{ij} is the AP association that needs to be decided in the next period.

A function $\theta(x_{ij}, x'_{ij})$ is introduced to indicate wether layer-2 handoff occurs, which is defined as follows:

$$\theta(x_{ij}, x'_{ij}) = \begin{cases} 1 & if\ x'_{ij} = 0\ and\ x_{ij} = 1 \\ 0 & otherwise. \end{cases}$$

If $\theta(x_{ij}, x'_{ij}) = 1$, it means interface i switch to AP j from a current associated AP. Noted that x_{ij} and x'_{ij} are 0-1 integers, the above equation equals to $\theta(x_{ij}, x'_{ij}) = x_{ij}(1 - x'_{ij})$.

Handoff decision is made at the beginning of each period T. If better AP association is found (according to the value of $\theta(x_{ij}, x'_{ij})$), it performs handoff by disconnecting from the current AP and reassociating to a new AP. Assume it takes T' time for a WiFi interface to disconnect and resume its network service. Typically the value of T' is less than a few seconds. In the measure of our testbed, $T' = 0.8$ second on average. If no handoff occurs in a period, $T' = 0$. After handoff, the mobile device moves freely in the rest $T - T'$ seconds without changing access points.

$$\begin{aligned}
Given: &\quad k\ WiFi\ interfaces,\ n\ APs,\ the\ threshold\ \xi,\ and\ the\ previous\ AP\ association\ x'_{ij} \in \{0,1\}, \\
max: &\quad \sum_{i}^{k}\sum_{j}^{n}\left[x_{ij}(1-x'_{ij})\int_{0}^{T'}\frac{g_{ij}}{1+e^{-\mu(t-t_0)}}dt + x_{ij}x'_{ij}g_{ij}T' + x_{ij}g_{ij}(T-T')\right] - \left[y'\hat{g}T' + y\hat{g}(T-T')\right] \quad (13) \\
s.t.: &\quad \sum_{j=1}^{n} x_{ij} \le 1, \quad (14) \\
&\quad \sum_{i=1}^{k} x_{ij} \le 1, \quad (15) \\
&\quad \frac{1}{T'}\sum_{i}^{k}\sum_{j}^{n}\left[x_{ij}(1-x'_{ij})\int_{0}^{T'}\frac{g_{ij}}{1+e^{-\mu(t-t_0)}}dt + x_{ij}x'_{ij}g_{ij}T'\right] + y'\hat{g} \ge \xi, \quad (16) \\
&\quad \frac{1}{T-T'}\sum_{i}^{k}\sum_{j}^{n} x_{ij}g_{ij}(T-T') + y\hat{g} \ge \xi, \quad (17) \\
&\quad \frac{1}{T}\sum_{i}^{k}\sum_{j}^{n}\left[x_{ij}(1-x'_{ij})\int_{0}^{T'}\frac{g_{ij}}{1+e^{-\mu(t-t_0)}}dt + x_{ij}x'_{ij}g_{ij}T' + x_{ij}g_{ij}(T-T')\right] > \sum_{i}^{k}\sum_{j}^{n} x'_{ij}g_{ij}, \quad (18) \\
&\quad x_{ij},\ y,\ y' \in \{0,1\}.
\end{aligned}$$

Fig. 10. Optimization problem of hybrid handoff decision with MPTCP.

We use the indicators $y', y \in \{0,1\}$ to denote whether 3G augmentation should be used during and after handoff. If $y' = 1$, 3G interface is turned on during layer-2 handoff; if $y = 1$, 3G interface keeps on after handoff.

The optimal handoff decision problem can be formulated as a maximization problem subjected to several constraints, which are shown in Fig. 10. The objective function and constraints are explained as follows.

In equation (13), the objective is to maximize the total WiFi downloads (in Mbits) and to minimize the 3G usage. The term $x_{ij}(1-x'_{ij})\int_0^{T'}\frac{g_{ij}}{1+e^{-\mu(t-t_0)}}dt$ denotes the download during handoff when W_i switches to AP_j. The term $x_{ij}x'_{ij}g_{ij}T'$ denotes the download in T' if no handoff occurs for W_i (i.e., $x'_{ij} = x_{ij} = 1$). The term $x_{ij}g_{ij}(T-T')$ indicates the downloads in $T-T'$. The sum of the three terms over all i and j yields the total WiFi download in the period T. The term $[y'\hat{g}T' + y\hat{g}(T-T')]$ forms the total 3G usage in T, where $y'\hat{g}T'$ and $y\hat{g}(T-T')$ represent the 3G augmentation during and after layer-2 handoff accordingly.

Several constraints need to be concerned for the problem. Equation (15) specifies that each interface should be associated to at most one AP. Equation (14) specifies that each AP should connect to at most one WiFi interface from the same device, which intends to reduce the contention of wireless channel and to fully exploit the opportunity of multipath transmission with MPTCP. Such constraint can be relaxed if there is short of APs in range. In equation (16), the left part indicates the average throughput of WiFi+3G during handoff. We let the left side larger than ξ, which guarantees that the throughput is higher than the predefined threshold. If the average WiFi throughput is lower than ξ, 3G augmentation will be used (i.e., $y = 1$) to satisfy the constraint. Similar, the left part of equation (17) indicates the average throughput in $T-T'$ (after handoff), which is required to be larger than the threshold ξ. In equation (18), the left part computes the estimated average WiFi throughput for the whole period T with the new AP association x_{ij}. We specify that it should be larger than the average throughput of the previous AP association $\sum_i^k\sum_j^n x'_{ij}g_{ij}$, otherwise there is no need to perform handoff.

TABLE I
EXECUTION TIME (MS) OF THE ALGORITHM.

	$n=5$	$n=6$	$n=7$	$n=8$	$n=9$
$k=3$	5.7734	6.2904	6.4819	6.6355	6.7674
$k=4$	6.0760	6.3170	6.5838	6.6552	6.7397
$k=5$	6.2233	6.5222	6.7193	6.6869	6.9893

Complexity and implementation concerns: The optimization problem is in the form of a typical 0-1 Integer Programming problem. Theoretically, solving this problem takes $O(2^{kn})$ complexity by exhaust searching. Fortunately, there exist exact algorithms such as *branch and bound* that can solve the problem with much lower complexity [24]. Moreover, existing mathematical programming toolkits such as CPLEX can be applied to solve Integer Programming problem efficiently. Since k is the number of network interfaces of a mobile device and n is the number of APs available in the mobile device's scanning range during a time period, k and n are small numbers in real network. Table I compares the execution time of the proposed algorithm using CPLEX with a laptop (Thinkpad T440, Intel i5-4200U 2.60GHz, 4GB RAM) under different n and k, which shows that most results return within 7ms, which is much shorter than the length of a time period (e.g., 10 seconds). Thus computation overhead is not a big issue for running the proposed roaming framework online.

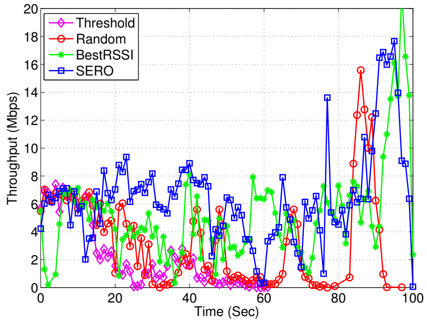

Fig. 11. Comparison of instantaneous WiFi throughput (single user).

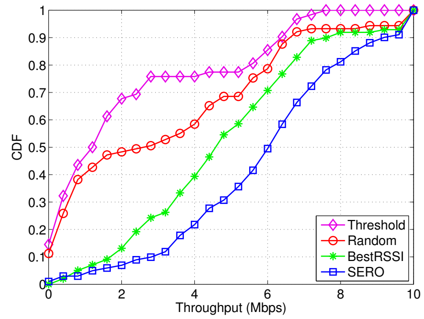

Fig. 12. Cumulative distribution function of throughput (single user).

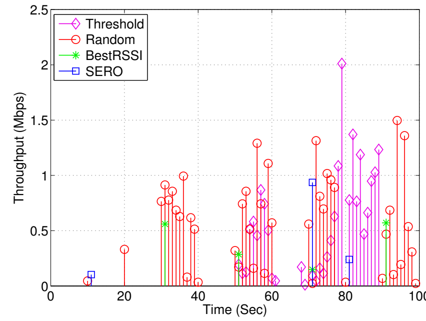

Fig. 13. Comparison of instantaneous 3G throughput (single user).

VI. Performance Evaluation

A. Comparison strategies

We implement the proposed SERO hybrid handoff framework in the WMN testbed introduced in section 3 and compare it with several heuristic handoff strategies:

- **Threshold:** Once an interface is associated to an AP, it will maintain the association as long as possible, and handoff occurs until the RSSI drops to a predefined threshold. This is the default handoff strategy implemented by most 802.11 commercial WiFi interfaces.
- **Random:** In each period, each WiFi interface is randomly associated to an AP in range. This strategy provides a baseline on the average performance of download.
- **Best RSSI:** Each WiFi interface is associated to the AP having the strongest RSSI value. Normally this leads to the association to the most proximate AP nearby. This strategy can obtain the best link quality, but it will cause frequent handoff if the APs are densely deployed.

3G augmentation is used for all the strategies to guarantee the minimum throughput. Once the monitor detects that the download throughput is below a threshold, 3G interface will be turned on, which allows MPTCP to create subflows for downloading via 3G network. The threshold of minimum throughput ξ is set to 100K byte per second, which is 0.8Mbps in our experiment.

During the experiments, several students hold mobile devices and walk along the hallway for several rounds to test the download throughput of different handoff strategies. In each round, the walking distance is 50 meters in the hallway, and the student tries to walk with a constant speed of one step per second. Every 10 seconds, the program makes handoff decision using the above mentioned strategies. The communication packets are logged using TCPdump for performance analysis.

B. Single user experiments

The first case we test the performance of the handoff strategies when there is only a single user in the system.

Fig. 11 shows the instantaneous WiFi TCP throughput of the four handoff strategies during an experiment. According to the figure, the instantaneous throughput of all strategies changes dynamically during walking. The threshold strategy

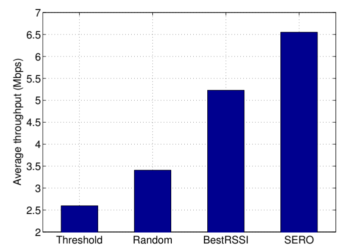

Fig. 14. Comparison of average throughput (WiFi+3G, single user).

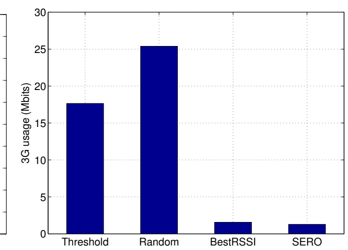

Fig. 15. Comparison of 3G usage (single user).

is the default strategy used by the interface, which appears a decreasing throughput when time passes. The reason is that it tries to maintain the original AP association as long as possible. Thus when the mobile device moves forward, the distance to the original AP becomes further, and the throughput drops lower. The throughput of random strategy is very diverse: it reaches very low or very high values at some points. The reason is that by randomly choosing AP to associate, the interface may connect to a very far away AP which yields low link quality, or connect to a proximate AP with high throughput. The bestRSSI strategy performs better than threshold and random, since it actively switches to the proximate AP with the best link quality. But it also performs handoff frequently, and the throughput drops to lower than 1Mbps at the time handoff occurs. The proposed SERO strategy outperforms the other strategies in most of time, and occurs much fewer handoffs than bestRSSI.

To show how well the proposed strategy can guarantee the minimum throughput threshold $\xi = 0.8Mbps$, we draw the cumulative distribution function (CDF) of instantaneous WiFi throughput in Fig. 12. The threshold strategy has more than 45% throughput values lower than 0.8Mbps, and about 10% approaches 0. The random strategy has 40% throughput lower than 0.8Mbps, and about 50% values distributes evenly between 3-7Mbps. The bestRSSI strategy has 6% throughput values lower than 0.8Mbps, and about 60% values are higher than 4Mbps. The SERO strategy has only 5% values lower than 0.8Mbps, and about 80% values are higher than 4Mbps.

Instantaneous 3G augmentation in the experiment is compared in Fig. 13. As shown in the figure, the threshold strategy generates a lot of 3G traffic after 50 seconds due to the reason that the mobile device moves far away from

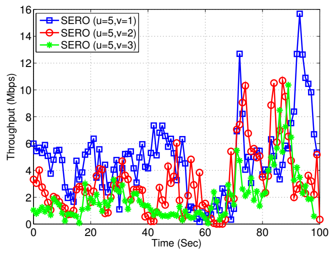

Fig. 16. Comparison of instantaneous WiFi throughput (multiple users).

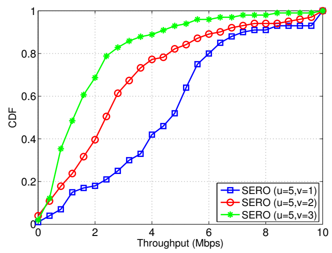

Fig. 17. Cumulative distribution function of throughput (multiple users).

the associated APs. For random strategy, 3G augmentation randomly appears in several time slots. BestRSSI and SERO use much less 3G traffic than threshold and random.

The average throughput of all wireless interfaces (including two WiFi interfaces and a 3G interface) are shown in Fig. 14. The average throughput of threshold, random, bestRSSI and SERO are 2.31Mbps, 3.14Mbps, 5.21Mbps, and 6.54Mbps accordingly, all of which are higher than the predefined threshold $\xi = 0.8Mbps$. The SERO strategy achieves the performance gain of 26% to 180% compared to the others.

The total 3G usage is illustrated in Fig. 15, which shows 17.65Mb, 25.38Mb, 1.57Mb, 1.28Mb for threshold, random, bestRSSI, SERO accordingly. As shown in the figure, the SERO strategy achieves the lowest 3G usage, which is only 81% of bestRSSI and only 5% of random.

C. Multiple user experiments

This case investigate the performance of SERO when there are multiple users in the WMN network. In the experiments, we place u smart phones in random places playing online videos. And there are v students holding laptops to walk along the hallway using SERO handoff strategy. We fix u and vary v from 1 to 3 to observe the system performance.

The instantaneous WiFi throughput and CDF are shown in Fig. 16-17 accordingly. When the number of users increases, the WiFi throughput drops due to the contention of communication channel. Still, throughput larger than threshold $0.8Mbps$ can be achieved in most of the time. When the number of users reaches to 8 ($u = 5, v = 3$), there are about 20% throughput values less than 0.8Mbps.

VII. Conclusion

In this paper, we address the handoff decision problem to enable seamless roaming in wireless mesh network with multipath TCP. We propose a handoff framework that exploits layer-2 handoff and vertical handoff to improve TCP throughput and smooth handoff interruption. To achieve these goals, we characterize TCP throughput based on measurement on a real-deployed wireless mesh network testbed. Using the knowledge of information theory, we derive the models to estimate the throughput of WiFi interfaces with and without handoff. We further propose a hybrid handoff framework called SERO, and formulate the handoff decision problem as a mathematical optimization problem which can be solved by Integer Programming. We implement the proposed SERO scheme in the WMN testbed to evaluate its performance. Extensive experiments show that the proposed optimal strategy outperforms the compared strategies with a performance improvement from 26% to 180%.

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