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# An Attractor Perturbation-Based Traffic Distribution Method and Its Practical Experiments

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**Abstract**—Nowadays, it is very common to see personal devices support two or more networking interfaces, e.g., for cellular networks, WiMAX, and Wi-Fi. In theory, a concurrent usage of a combination of multiple radio access technologies (RATs) can provide low-cost high performance communication, i.e., lower delay and higher throughput. However, there is a problem of how to distribute traffic over the different network interfaces to maximize the gain and adapt to changes in traffic patterns. In this paper, we tackle this problem by using an attractor perturbation-based method which utilizes end-to-end information including fluctuations to distribute traffic over different network interfaces to increase the available bandwidth while trying to minimize the average end-to-end delay. We also include results from practical experiments to show the performance of our proposal.

## 1. Introduction

In recent years, mobile devices are equipped with more than one networking interfaces which can use different radio access technologies (RATs), e.g., Wi-Fi, WiMAX, 3G/LTE, etc., see Figure 1. Since the cellular network capacity has its limitation, in terms of both available bandwidth and economic aspects, several proposals [1] have been made to concurrently use other RATs, mostly involving Wi-Fi due to its wide availability for free or low cost, to improve communication performance when possible. Another usage of multiple RATs is to reduce horizontal handover time by performing a vertical handover which has its advantage over MobileIP [2] in terms of implementation simplicity without infrastructure changes [3].

Most bandwidth aggregation methods operate on network and transport layers [1]. However, similar to the difficulties in IP addressing faced by MobileIP [2], the network layer implementation should be avoided. On transport layer, a lot of methods are implemented over SCTP [4] which is similar to TCP but also natively supports multi-homing, allowing connections between a set of IP addresses instead of only a pair. However, SCTP does not support concurrent usage of multiple paths at the moment.

In order to improve the communication performance, most proposal rely heavily on estimating the network condition on each RAT (or each possible path) by using probing results that are instantaneous and consume more bandwidth at a high probing frequency. Therefore, we propose the use of a bio-inspired mechanism, called attractor perturbation (AP), which utilizes end-to-end statistical information instead of simple probing to reduce bandwidth consumption. AP can provide a simplified view of the network as a black box with only the end-to-end observed variables while maintaining the ability to control the network to reach a better performance. Moreover, AP takes fluctuations into consideration similarly to other bio-inspired mechanisms which are known for their adaptability. Hence, a higher adaptability can be expected when compared to traditional methods.

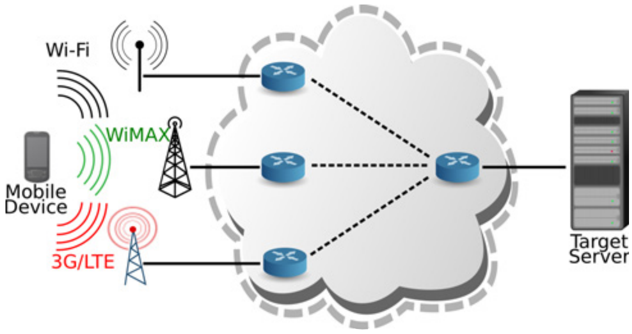



Figure 1: Overview of target system with multiple RATs

The rest of this paper is organized as follows. We first explain the bio-inspired attractor perturbation model in Section 2. Next, we describe the usage of AP in our proposal in Section 3. Then, the implementation details on real devices and the experimental results are presented and discussed in Section 4. Finally, we conclude this paper and describe future work.

## 2. Attractor Perturbation

In an attempt to design new adaptive networking mechanisms, proposals based on biological mechanisms [5, 6] have been made for self-organized control since such mechanisms are able to provide greater robustness and adaptability to external influences. In this paper, we consider a bio-inspired model called attractor perturbation (AP).

The attractor perturbation model is derived from observations of fluctuation and response in biological systems, which are typically given as nonlinear dynamic systems and experimentally observed in the evolution of functional proteins in a clone bacteria cell. In [7], it was found that the fluctuation, which is expressed by the variance of the fluorescence of a bacterial protein, and its response, which is the average change in this fluorescence against an applied force, have a linear relationship modeled as follows:

$$\bar{x}_{a+\Delta a} - \bar{x}_a = b\,\Delta a\,\sigma_a^2 \tag{1}$$

where $b$ is a scalar constant, $x$ is a time dependent measurable variable in the system with mean $\bar{x}$ and variance $\sigma_a^2$, and $a$ is the amount of force applied to the nonlinear biological system. The attractor perturbation model is similar to the fluctuation-dissipation theorem in physics [8].

There are two major assumptions underlying the model formulation of AP. First, the variable $x$ must have a Gaussian-like distribution which is often observed in biology. Second, the variable $x$ and the force $a$ are closely associated, in other words, a change in the force $a$ would strongly affect the distribution of the variable $x$.

Equation (1) reveals that the difference in the average of the variable $x$ before and after applying a change to the force $a$ is linearly proportional to the amount of change in $a$ and the variance of the variable $x$ prior to the change. Therefore, one can predict the response to the applied force from the knowledge of the fluctuation of the targeted system. Since the amount of change in $a$ can be seen as controllable, it is possible to adjust the difference in average of $x$, called *perturbation*, by taking the current variance of $x$ into consideration. Obviously, using the same amount of force $\Delta a$ to perturb the average of $x$ when the variance $\sigma_a^2$ is large will also lead to a larger perturbation. More details on the AP mathematical model are available in [9].

## 3. Concurrent Multipath Traffic Distribution

AP has been used to implement a rate control mechanism to stabilize end-to-end delay in wired networks [10] and also for a traffic distribution over multiple paths in ad hoc networks [11]. This study is an extended version of [11] to a multihoming problem with additional practical experiment results.

In our proposal, we map the observed variable $x$ in the attractor perturbation model to *end-to-end delay* of packets and the force $a$ to *traffic rate*. In our preliminary experiments, we confirmed that the distribution of end-to-end delay roughly followed a Gaussian distribution and there was a linear relationship between changes in end-to-end delay and traffic rate. Our proposal aims at minimizing the average end-to-end delay of all packets by setting the appropriate traffic rate. Using AP, we attempt to minimize the *total delay sum*, which directly corresponds to the average delay of all packets on all paths (all RATs). The delay sum can be estimated through the product of the expected delay and the adjusted traffic rate on each path. Therefore, the minimization problem can be formulated as in Eqn. 2 and can be solved using the Lagrangian. Moreover, Eqn. 2 can be easily extended to cases with $n > 2$.

**Minimize**

$$f(\Delta a_1, \Delta a_2) = \Sigma_{i=1}^2 \left[ (\bar{x}_i + b_i \Delta a_i \sigma_i^2) \times (a_i + \Delta a_i) \right] \tag{2}$$
$$\textit{subject to} \quad \Sigma_{i=1}^2 \Delta a_i = 0$$

The optimal solution $\Delta a_i^*$ from Eqn. 2 solved using the Lagrangian technique is used in the following procedure (Alg. 1) and is executed at the source periodically.

**Algorithm 1** AP-based Traffic Distribution

**procedure** AdjTraffic($\bar{x}_1, \sigma_1^2, a_1, \bar{x}_2, \sigma_2^2, a_2$)
    $(\Delta a_1^*, \Delta a_2^*) \leftarrow$ SolveMinProb($\bar{x}_1, \sigma_1^2, a_1, \bar{x}_2, \sigma_2^2, a_2$)
    **if** $|\Delta a_1^*| > \alpha_{\max} \times (a_1 + a_2)$ **then**
        $\Delta a_1^* \leftarrow \alpha_{\max} \times (a_1 + a_2) \times \frac{\Delta a_1^*}{|\Delta a_1^*|}$
        $\Delta a_2^* \leftarrow -\Delta a_1^*$
    **end if**
    $a_1 \leftarrow a_1 + \Delta a_1^*$
    $a_2 \leftarrow a_2 + \Delta a_2^*$
**end procedure**

Algorithm 1 uses only the traffic sending rate on each path and the statistical information, i.e., average delay $\bar{x}_i$ and delay variance $\sigma_i^2$, from the destination which is sent back to the source once every periodic interval. First, the minimization problem (see Eqn. 2) is solved using the Lagrangian technique to obtain the optimal solution of the amount of traffic rate needed to be adjusted on each path: $\alpha_i^*$. Next, we gradually apply the optimal solution in small steps, limited by $\alpha_{max}$, to avoid fluctuations that might occur due to a sudden change in traffic rate. We use $\alpha_{max} = 10\%$ of total rate in this study.

## 4. Implementation and Evaluation

In this section, we describe how we implemented our AP-based traffic distribution method on off-the-shelf equipment and how we carried out the experiments in detail.

### 4.1. List of Used Equipment

**Server Side**

- Linux laptop (Ubuntu 12.04 64 bit)
- Internet connection via LAN interface through CATV (DOCSIS) ISP (J:Com) with maximum 160 Mbps downstream and 10 Mbps upstream.

**Client Side**

- Linux laptop (Ubuntu 12.04 64 bit)
- Internet connection: WiMAX (UQ WiMAX), maximum 40 Mbps downstream and 15.4 Mbps upstream, via NEC Aterm WM3500R mobile router.
- Android phone with USB tethering capability (LG Optimus G with Jelly bean 4.1.2)
- Internet connection: LTE (Softbank emobile), maximum 42 Mbps downstream and 5.7 Mbps upstream, via ULTRA WiFi SoftBank 007Z mobile router.

### 4.2. Experiment Environment

Since the current off-the-shelf Android devices do not support SCTP nor the concurrent multipath transfer protocol, we decided to set up a comparable environment by emulating mobile device characteristics. In place of an Android device, we use a Linux (Ubuntu) laptop, which shares a similar kernel architecture as Android. Mobile devices usually have two or more non-interfering RATs per device and we use portable routers to imitate multiple RATs. To avoid interference between two devices, separate channels are used on each Wi-Fi connection. Since the laptop has only one wireless interface, we use a combination of an Android phone connected to one of the two portable routers via Wi-Fi and connect the phone to the laptop using USB tethering. The experiment environment is shown in Fig. 2.

### 4.3. Implementation Steps

In the implementation of our proposal, the original session's total traffic rate is split equally into two UDP sessions and sent to the destination via two different interfaces for a period of 5 seconds. After the transmission period ended, the source requests statistical information on traffic from the destination and the destination sends the average and variance back to the source. The source then uses Alg. 1 to calculate the required traffic rate adjustment and resends the traffic using the adjusted rate on two UDP sessions for another 5 seconds and these steps are repeated until the end of the original session.

To generate UDP traffic and measure throughput and delay, we modified an open source Internet performance measurement tool (Iperf) version 2.0.8 [12] to not only report throughput but also average delay and delay variance between the client and the server. The generated traffic from Iperf is modeled after a Skype video call based on [13, 14], where the UDP packet size is 500 bytes and the total traffic rate for a HD video call is 1.5 Mbps (≈1500 Kbps in our implementation).

Since *one-way* end-to-end delay is used in both Iperf and our proposal, we ensure the correctly measured one-way delay by setting up an NTP server on the Iperf server and an NTP client on the Iperf client, which periodically synchronizes the time of the client to that of the server.

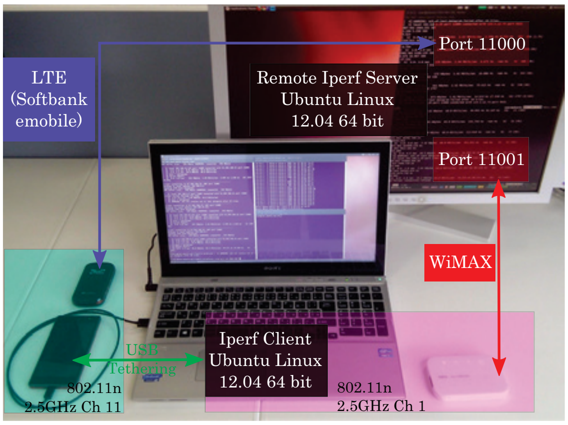



Figure 2: Experiment environment

### 4.4. Comparison Target

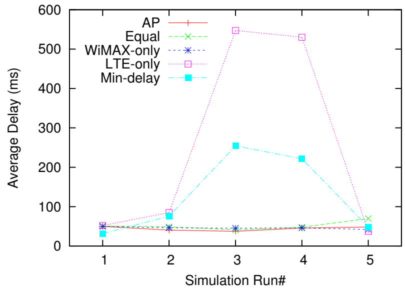
In addition to our proposal, we also evaluate four other traffic sending patterns, which are 1) sending only on the LTE interface (*LTE-only*), 2) sending only on the WiMAX interface (*WiMAX-only*), 3) sending equally on both LTE and WiMAX (*Equal*), and 4) sending with almost total traffic rate on the path with lower measured average delay on the previous transmission period and sampling the average delay on the other path with minimum rate of 64 Kbps (*Min-delay*).

We perform experiments using each approach in the following rotation: AP→Equal→WiMAX-only→LTE-only →Min-delay. The reason is to let every approach experience the same or the most similar network conditions.

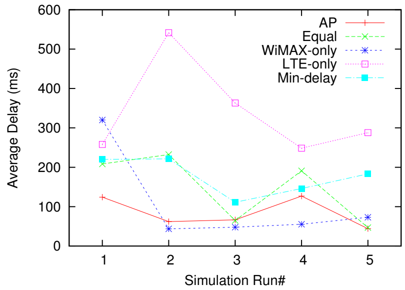
### 4.5. Results

We repeat experiments with a 100-second long session with traffic rate of 1500 Kbps 5 times and show the results in Fig. 3(a) and Fig. 4(a). It can be seen that LTE has a much lower tolerance to burst traffic. Therefore, there are cases that high congestion occurs and delay surges, and as a result, the throughput of LTE-only decreases. The Min-delay approach also suffers high delay because a sudden traffic rate change on the LTE path causes congestion and drastically increases delay the same way as in the case of LTE-only. Other approaches could handle the low traffic rate quite well. Consequently, we further perform experiments at higher traffic rates.

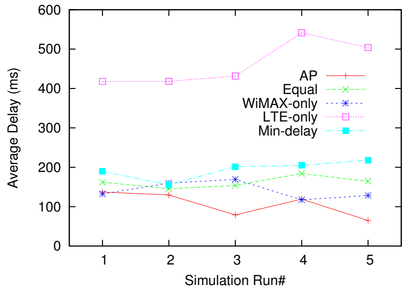
With higher bit rates, it can be seen that LTE becomes a bottleneck where delay increases and throughput decreases drastically. AP is useful in this case because it does not require any knowledge regarding the underlying type of interface. AP does not know in advance which path is WiMAX or LTE, nor which path has a higher bandwidth. As a result, it is adaptive and could achieve nearly the same performance as using the best path of WiMAX-only, and better performance when the total traffic rate exceed WiMAX actual throughput as shown in Fig. 3(c) and Fig. 4(c).




(a) Total traffic 1500 Kbps

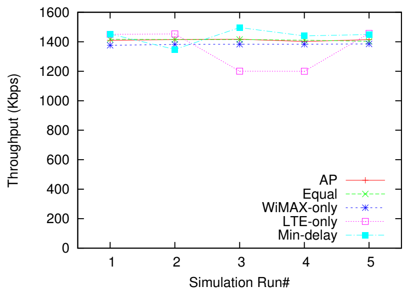



(b) Total traffic 5000 Kbps

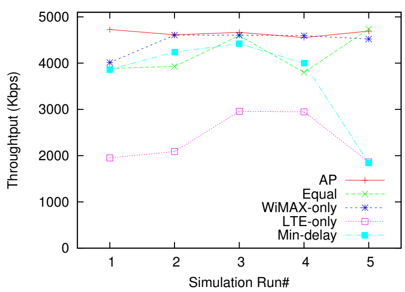



(c) Total traffic 7000 Kbps

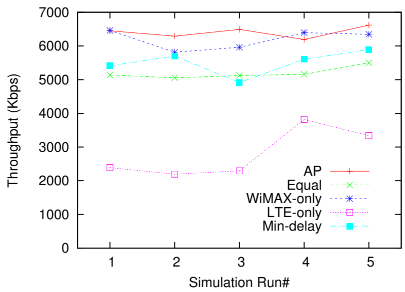
Figure 3: Average end-to-end delay results




(a) Total traffic 1500 Kbps




(b) Total traffic 5000 Kbps




(c) Total traffic 7000 Kbps

Figure 4: Throughput results

## 5. Conclusion

In this paper, we proposed a concurrent multipath traffic distribution method which uses only end-to-end delay statistical information without knowledge of bandwidth, loss rate, or other characteristics of underlying paths. Based on real world experiments using Linux machines, it has been shown that the AP-based method can achieve comparable delay and throughput as using the best path when it can handle the total traffic without loss. In case of a traffic rate higher than a single path's bandwidth, the AP-based method can shift portions of the total traffic onto another path to avoid congestion and loss, which is a desirable feature for both users and Internet service providers. In the future, we plan to implement the proposal as a mobile application.

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