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アドホックネットワークにおけるマルチパストランスポートプロトコル

Mehdad N. Shirazi† 内藤壮司‡ 美濃導彦†

†独立行政法人　情報通信研究機構 〒619-0289 京都府相楽郡精華町光台 3-5
‡富士通関西中部ネットテック 〒 大阪市中央区城見 2-2-53

概要 アドホックネットワークはユビキタスサービスの実現において重要な技術となりつつある。しかしアドホックネットワークプロトコルは限定された環境で動作する事を前提に設計されたプロトコルであり、インターネット上における全てのサービスをアドホックネットワーク上でサポートできることが困難である。有線ネットワークにおいてはサービス品質の向上を目的とする技術としてマルチパス通信方式は提案されている。また、複数のネットワークカードを同時利用する形態においてはその有効性は示されている。しかし、アドホックネットワーク上のマルチパス通信は、干渉による問題があり総合的に評価されていない。本研究では、アドホックネットワーク上でマルチパス同時通信をサポートする為にトランスポート層のプロトコルである SCTP を拡張する方式を提案する。本プロトコルは動的に変化するルートの状態を管理し、ルート状態に基づいて確認応答をベースとする同時転送制御を行う。また、シミュレータ(NS-2)による実装を行い、シミュレーション実験によりアドホックネットワーク上での同時通信方式の評価を行う。

A transport protocol for Multipath Communication in Ad-hoc networks

Mehdad N. Shirazi† Shoji Naito‡ Michihiko Mino†

†National Institute of Information and Communication Technology
‡Fujitsu Kansai Chubu Net-tech

Abstract Wireless mobile ad hoc networks, with self-organizing and fast deployable features, are making a promising technology towards the realization of a ubiquitous network environment. However, the realization of ubiquitous services would not be easily achieved due to the dynamic nature of network topologies, resource constraints of terminals, and constraints of wireless medium. Multipath routing is known as a technique to increase end-to-end throughput and provide load balancing in wired networks. However, its advantage is not obvious in wireless ad hoc networks because the traffic between multiple paths may interfere with each other. Indeed, recent works showed that concurrent transmission over multiple routes indeed leads to performance degradation, rather than bandwidth aggregation, when reliable ACK-based protocols are used at the transport layer. In this paper, we evaluate the issues involved and propose a cross-layer scheme to get around the problems that conventional transport protocols encounter when data are transmitted concurrently over multiple routes in mobile wireless ad-hoc networks. In this scheme, transport protocol is informed of the available routes, which change dynamically over time, through an interface with the underlying routing protocol. The transport protocol performs a concurrent reliable and in-order delivery of data over the available paths based on a route-based congestion and retransmission control. The proposed scheme is implemented on ns-2 network simulator and evaluated through simulation studies.

1 Introduction

Mobile Ad doc Networks (MANETs) consist of a collection of wireless mobile nodes, which form a temporary network without the reliance on a fixed base station or a wired backbone network. MANETs are typically distinguished by the high degree of mobility and the limited power, processing and memory resources of nodes. Also, due to the limited transmission range of wireless nodes, transmission over multiple hops is usually needed to exchange messages between nodes. Route failures happen very frequently due to node mobility, unreliability and unpredictability of wireless links, multi-hop transmission, and the fact that nodes may dynamically leave and join the network.

In MANETs, due to the limited resources of nodes, it is desirable that a routing protocol fairly distributes traffic among the nodes (load-balancing). An unbalanced assignment of traffic will lead to congestion, higher end-to-end delay and power depletion in heavily loaded nodes. Multipath ad hoc routing protocols are considered effective in this aspect due to their load-balancing feature, which is achieved by routing traffic over multiple paths.

Fault tolerance to route failure is another desirable feature for MANETs. It is usually achieved by equipping routing protocols with mechanisms for route failure detection and subsequent route discovery. Unipath routing protocols, however, suffer from frequent route discovery and high route discovery latency. Frequent route discovery attempts largely increases the routing overhead caused by the broadcast of route request messages, which in turn increase network load and route failure rate. Multipath routing protocols alleviate these problems by preemptively search for multiple paths at each route discovery attempt or by extracting and cashing the route information through mechanisms such as overhearing.

The other issue is the low capacity of wireless medium. Stripping data over multiple paths, as a mean to achieve bandwidth aggregation, has been shown to be effective in the context of wired networks. However, the subject has not been investigated thoroughly in the context of wireless ad hoc networks. Basically, it would be difficult to achieve bandwidth aggregation in MANETs due to the coupling of routes; i.e., routes are coupled when they are located physically close enough to interfere with each other during data transmission. The interference between routes, in a wireless medium, increases collision and packet losses, which not only reduce goodput but also lead to instability of routes (routes exists only over short time intervals). The route-coupling problem might be alleviated by imposing constraints such as route disjointness, using multiple non-interfering channels, or by using directional antennas. In [1] authors showed that, using directional antennas, bandwidth aggregation can be achieved over MANETs.

Route coupling is not, however, the sole issue faced by concurrent multipath data transmission schemes. As the previous works [2] have shown, concurrent multipath routing leads to throughput degradation, rather than bandwidth aggregation, when traffics run over TCP. In this paper, we consider the issues and evaluate the potentiality of concurrent data transmission over multiple paths in the context of MANET. We present a cross-layer scheme where the transport and routing protocols exchange routing information and are modified to support concurrent reliable and in-order data transmission over a dynamically changing set of available paths. The protocol, through an interface with an underlying ad hoc routing protocol, monitors the number and state of the available routes. The flow control, congestion control, and efficient retransmission control of data are achieved through a route state-transition mechanism. This mechanism takes into account the frequent occurrence of route failures, unavailability of a route to a destination during data transmission, and the status of outstanding data over available routes.

The rest of the paper is organized as follows. Section 2 introduces related works. In section 3, we point out the issues which arise when data are transmitted concurrently over multiple paths in MANET. Section 4 introduces the proposed cross-layer approach which enables a properly designed transport protocol to monitor and control concurrent data transmission over available paths. Section 5 gives the design of such a protocol. We present the results of our preliminary simulation studies in section 6 and conclude the paper in section 7.

2 Related Works

Data stripping across multiple network paths has been explored in several different contexts in the past. It has attracted attention due to its desirable features such as load balancing, fault tolerance, and bandwidth aggregation. Multiple network paths can be made available to an application by using multiple network interfaces (multi-homing) or using multiple routes between a pair of network interface at the source and destination nodes. The former approach, where the endpoints of a connection are assumed to be equipped with multiple network interfaces, was proposed basically for infra-based networks [3][4][5]. As compared to these works, where there is no interference between paths, we consider here concurrent data transmission over wireless mobile ad hoc networks where factors such as instability of routes, routing overhead, and interference between paths affects the effectiveness of multi-path routing to a large extend.

The latter approach to provide multiple network paths, on the other hand, was mainly proposed as multipath routing solutions in the context of wireless mobile ad hoc networks [6][7][8]. The main focus of these works was to impose diversity and disjointness on the cached routes. Though, these works revealed the adverse effect of route coupling and came up with ways to alleviate it, they did not detail on the feasibility of having multiple stable routes to a destination node, which is a prerequisite for concurrent data transmission. Moreover, most of these protocols use multiple routes in a backup mode, where an alternative route is used only when the currently used one fails.

In [7], authors proposed an extension of DSR protocol, called Split Multipath Routing (SMR), which supports concurrent data routing over a set of link-disjoint paths. The simulation studies in [7] compared performance of SMR against DSR. However, because DSR protocol has stale route problem it is hard to evaluate the potentiality of concurrent multipath routing in MANET based on the provided results. Moreover, the simulation results are based on experiments with UDP traffics where out-of-order packet delivery affects only reordering delay at the receiver queue. In another work [2], the authors showed that, induced by packet reordering, concurrent multipath routing indeed results in performance degradation when TCP is used as the transport protocol. They, hence, proposed a backup version of SMR to get around the adverse effect of out-of-order packet delivery on TCP performance. Still in another work, they proposed some modifications of TCP to alleviate the problem [9]. We believe that a clean and effective solution needs for a cross-layer approach with proper modifications at the both routing and transport protocols.

3 Concurrent Multipath Data Transmission in MANET

Several issues arise when reliable transport protocols (TCP / SCTP) run over a concurrent multipath routing protocol. One issue is that the RTT estimation is never accurate. Specifically, different delays on different paths lead to incorrect RTT estimate and RTO setting. Incorrect setting of RTO, in turn could incur premature timeouts on the longer paths, which lead to redundant triggering of congestion and retransmission control mechanisms. Moreover, it is likely that packets going through different paths arrive at destination out-of-order. Out-of-order packets trigger duplicate ACKs, which in turn cause unnecessary triggering of fast retransmit / recovery mechanisms. We extend SCTP protocol, as detailed in the next section, to support concurrent multipath data transmission without incurring such malfunctioning.

Another issue is frequent occurrence of link failures. Link failures largely degrade TCP / SCTP performance due to the reduction of congestion window and progressive increase in RTO, which could lead to unacceptably low throughput (particularly when routing protocol has stale route problem). A solution is to detect link failures and freeze TCP state, including congestion window and RTO, until a new route is re-established [10]. Our scheme suppresses the occurrence of RTO's exponential back-off over deployed routes, as a side effect of the adopted cross-layer approach. Specifically, the state of a route is partially frozen or deleted according to a route state-transition mechanism, which takes into account both the route state notified by the routing protocol and the state of the data that has been transmitted over the route.

The other issue is the increased contention caused by the concurrent use of multiple paths instead of a single path. This increase in contention adversely affects stability of routes, which is a prerequisite for a concurrent multipath data transmission scheme. Though, this problem can be alleviated by imposing constraints on the number of routes that a routing protocol can cash and use per destination, our simulation results showed that such measures are not good enough to ensure route stability. To ensure route stability, we modified SMR routing protocol such that route discovery is performed periodically while still preserving on-demand nature of the protocol.

4 A Cross-layer Approach

To address the issues mentioned above, we propose a cross-layer approach with corresponding modifications at both the routing and transport protocols.

4.1 System architecture

Figure 1 shows the architecture of the proposed ad-hoc multipath communication system. In this system, concurrent multiroute transport protocol (CMP-TP) performs simultaneous transmission of data over a dynamically changing number of routes in a reliable and in-order way. The socket interface between CMP-TP and application is extended to support backward compatibility. Specifically, during the connection initialization, both endpoints have to explicitly inform the peer endpoint whether they support CMP-TP or not. The underlying routing protocol manages the dynamically changing route information and provides it to CMP-TP through a route information interface, which is implemented as an extension of kernel's API. Based on the information about available routes and their states, CMP-TP determines, and specifies in the packet's header, the route over which the packet should be transmitted.

4.2 Multipath routing protocol

Within the proposed cross-layer scheme, a multipath ad-hoc routing protocol needs to be augmented by the following functionalities; 1) assignment of IDs to cashed routes, 2) notifying CMP-TP of newly added routes, 3) notifying CMP-TP of routes removed from the cash, and 4) routing packets according to the route ID which is specified by CMP-TP in the packet header.

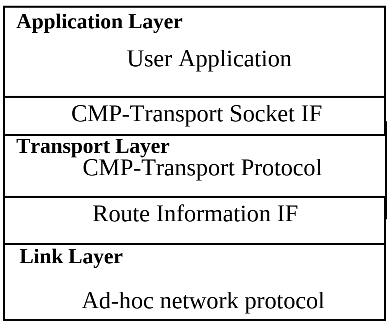

Figure 1 System architecture

These functionalities are orthogonal to basic routing functionalities such as route discovery and management and hence can be added to various multipath routing protocols. We actually implemented these functionalities to the DSR and SMR protocols, which are backup multipath and concurrent multipath routing protocols, respectively.

4.3 Concurrent multipath transport protocol

Reliable transport protocols are equipped with congestion, retransmission, and flow control mechanisms in order to provide a reliable in-order delivery of data to a network application. SCTP basically inherits the mentioned mechanisms from TCP with some extensions to deal with its multi-homing, multi-streaming, and message-oriented features.

As mentioned before, concurrent data transmission over multiple paths degrades the performance of reliable ACK based protocols. These are mainly caused by the inaccuracy of RTT estimates and out-of-order arrival of packets. These problems could be avoided if the transport protocol being able to estimate RTT and to monitor out-of-order packet arrival per path rather than per connection. Moreover, the congestion and retransmission control mechanisms should be separated from the flow control mechanism and should be performed per path basis. These are obvious noting the role that these mechanisms perform within a reliable transport protocol. Specifically, the role of congestion control is to avoid congestion in the network by throttling down the connection throughput when congestion occurs over the path it uses. Since congestion is a path dependent event, congestion over a path should not trigger congestion control over other paths. Otherwise, congestion over a single path throttles down the transmission over even those paths which are not experiencing congestion.

Packet retransmission is triggered when a packet loss indication is detected at the sender endpoint. TCP and SCTP use the following events as a packet loss indication; 1) arrival of 3 duplicate ACKs (4 duplicate SACKs in case of SCTP), 2) occurrence of retransmission timeout. The former mechanism for detecting loss indication is based on sequence numbers associated with packets and the latter is based on estimates of RTT. In the context of concurrent multipath data transmission, performing RTT estimates and associating sequence numbers per connection rather than per path could lead to false occurrence of timeouts and duplicate ACKs (SACKs). This in turn can lead to unnecessary retransmission of packets as well as reduction in the congestion window.

Though flow control should remain at the connection level, the asynchronous existence of outstanding data over different paths needs for proper modification of the flow control mechanism.

5 CMP-TP Architecture

In this section, we present the architecture of the concurrent multipath transport protocol. SCTP protocol is deployed as a vehicle for implementation and is extended such that to encompass the features, which were identified in the previous section as being desirable for a concurrent multipath transport protocol. Hereafter, the protocol is referred to as CMP-SCTP.

5.1 Congestion and retransmission control

To avoid the issues mentioned above, the SCTP's data-chunk format is extended to include Route ID (RID) and Route Sequence Number (RSN). RID is used to identify the route over which a data chunk is transmitted. RSN is used to uniquely identify a data chunk among those transmitted over the same route. After determining the route which be used for transmission a data chunk, the sender endpoint insert the RID and RSN in the chunk's header. For an arrived data chunk, the receiver endpoint returns a SACK control chunk that includes RID, cumulative RSN, and gap ACK blocks. CMP-SCTP maintains a data structure per route, to make simultaneous control and retransmission control per route feasible. This data structure maintains the congestion and retransmission control variables including congestion window size, slow-start threshold, round trip time, retransmission timeout, outstanding data, and partial bytes acknowledged. Other variables such as receiver window size and total outstanding data count are related to the flow control and are hence maintained per association. In CMP-SCTP, for each available route there is a corresponding route manager module at both the sender and receiver endpoints. Each module performs updating of the data structure of the corresponding route and manages the congestion and retransmission of data chunks over the route.

5.2 Flow control

To avoid buffer overflow, the sender endpoint has to monitor the association buffer at the receiver endpoint and regulate the transmission rate accordingly. In SCTP, the sender endpoint is notified of the available buffer space at the receiver endpoint through SACK chunk information. The sender endpoint subtracts the notified receiver's buffer space from outstanding bytes (data that has been transmitted but not yet acknowledged) and determines the amount of new bytes of data that can be transmitted at that point, without incurring overflow of the receiver buffer.

In CMP-SCTP, the management module of a route is not aware of the holes that might have been occurred in the RSN of other routes. Since data transmission over available routes is asynchronous, transmission of new data chunks over a route, based on outstanding bytes calculated over that route, can lead to the overflow of the receiver buffer. In CMP-SCTP, this problem is avoided by using the total outstanding bytes over all available routes. Upon arrival of a SACK control chunk, the permissible amount of data transmission over the corresponding route is calculated using the receiver's available buffer space and the total outstanding bytes.

5.3 Other considerations

Some of the parameters of a route data structure should be synchronized between the sender and receiver endpoints. The sender endpoint sends a control chunk (Heartbeat) to inform the receiver endpoint of the RID of a newly added route and the initial RSN used by the route. The receiver endpoint acknowledges this information by sending back a corresponding control chunk (Heartbeat-ACK). A Heartbeat control chunk is retransmitted if its timer expires.

When a route fails, there is a need for delegating delivery of its outstanding data to other available routes. However, to avoid unnecessary retransmissions, delegation should be confined to only those outstanding data chunks that would not successfully get delivered to the peer endpoint.

In MANET, routes failure could happen so frequently that for some time intervals the cash of the routing protocol may have no route item for a given destination. Hence, there is a need for a mechanism that ensures triggering of the route discovery mechanism of the underlying route protocol. For this purpose we augmented CMP-SCTP with a virtual route. The virtual route also serves the purpose of handling the outstanding data chunks of a failed route while there is no other established route available.

In CMP-SCTP, the proper operation of these mechanisms is based on a route state-transition mechanism that keeps track of the state of routes as well as their outstanding data chunks.

6. Simulation results

In this section, we evaluate the performance of the proposed cross-layer scheme using ns-2 network simulator [11]. The following setup was used in our simulation studies.

The distributed coordination function of IEEE 802.11 was used as the MAC layer protocol. The channel capacity was set to 11 Mpbs, number of mobile nodes to 50, and the region size to 1000m x 1000m. Initial location of nodes, which is different for different simulation runs, was determined using a uniform distribution. Each node moves independently with the same average speed according to random waypoint model. In this mobility model, a node randomly selects a destination from the physical terrain. It moves to the destination in a speed uniformly chosen between the minimal and the maximal speed. After it reaches its destination, the node stays there for a pause time and then moves again. In our simulation, we used 10 m/s, 20 m/s, and 30 m/s as the node's mobility. Simulation time was set to 600[s], 300[s], and 200[s] to isolate mobility effects from topological factors. For each experiment, fifty runs with different random seeds were conducted.

We compared the performance of concurrent multipath data transmission scheme, where CMP-SCTP protocol runs over MP-DSR routing protocol, against unipath data transmission scheme, where SCTP protocol runs over DSR. Figure 2 shows the simulation result for unipath data transmission. The horizontal and vertical axes show the expected and measured goodput of SCTP protocol respectively. The distance between a plotted point and the diagonal line shows the difference between the expected and measured goodput for a simulation run. As can be seen, there is a large difference between the expected and measured values in average and there is also a large difference in variance of measured goodput, particularly when node mobility is high. By analyzing the simulation results, it was found that the low goodput was largely induced by the occurrence of exponential backoff (Figure 3).

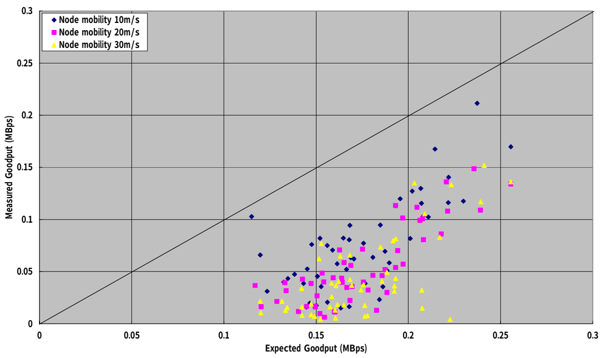

Fig. 2 Performance of unipath scheme

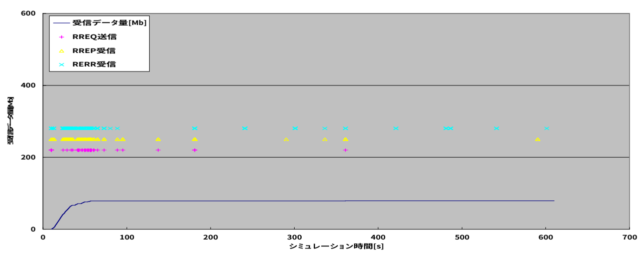

Fig. 3 Data delivery under unipath scheme

Figure 4 shows the simulation result for the concurrent multipath data transmission scheme. It can be seen that the difference between the expected and measured goodputs are not as high as the unipath transmission scheme. Moreover, concurrent multipath transmission scheme showed more stable performance in terms of the goodput variance over performed simulation runs. Analysis of simulation results showed that exponential backoff does not occur as frequently as in the unipath transmission scheme (Figure 5). This is due to the simultaneous use of multiple routes, which reduces the time needed to detect stale routes.

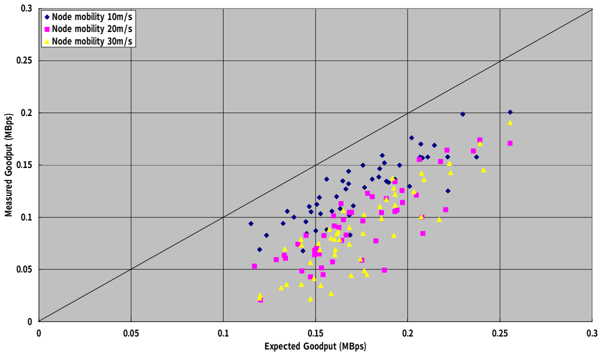

Fig. 4 Performance of concurrent multipath scheme

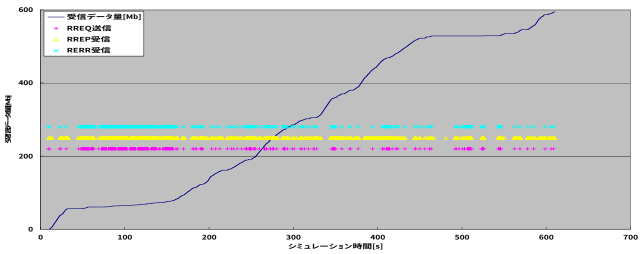

Fig. 5 Data delivery under concurrent multipath scheme

Figure 6 shows the average goodput achieved when the number of traffics was increased. It was observed that the goodput of the concurrent multipath transmission scheme degrades more sharply than the unipath transmission scheme when number of traffics is increased. This sharp performance degradation was found to be caused by three factors, 1) DSR routing protocol cashes a potentially large number of routes per destination, 2) DSR does not impose any sort of diversity constraints on cashed routes, and 3) concurrent transmission over a large number of correlated routes can easily lead to a high level of interference in the wireless network.

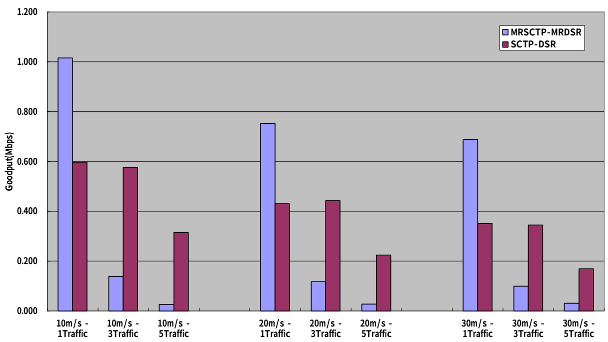

Fig. 5 Average goodput for variable number of traffics

Conclusions

We presented a cross-layer approach to alleviate the problems that surface in mobile wireless ad-hoc networks, when data are transmitted concurrently over multiple routes. As compared to previous works, the problems were identified and studied at both the routing and transport protocols. It appeared that, the cross-layer nature of the proposed scheme is effective in alleviating the stale route problem of the conventional routing protocols such as DSR. Simulation results also revealed that, though bandwidth aggregation can be achieved in principal, the low capacity of the existing wireless medium severely degrades its potentiality.

It would be desirable to embed a mode selection mechanism at routing protocol to estimate the level of contention over paths used by a node and switch between back-up and simultaneous data transmission modes.

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