Auction-Based Schemes for Multipath Routing in Selfish Networks

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Abstract—We study multipath routing with traffic assignment in selfish networks. Based on the Vickrey-Clarke-Groves (VCG) auction, an optimal and strategy-proof scheme, known as optimal auction-based multipath routing (OAMR), is developed. However, OAMR is computationally expensive and cannot run in real time when the network size is large. Therefore, we propose sequential auction-based multipath routing (SAMR). SAMR handles routing requests sequentially using some greedy strategies. In particular, with reference to the Ausubel auction, we develop a water-draining algorithm to assign the traffic of a request among its available paths and determine the payment of the transmission in approximately constant time. Our simulation results show that SAMR can rapidly compute the allocations and payments of requests with small sacrifice on the system cost. Moreover, various sequencing strategies for sequential auction are also investigated.

Index Terms—Auction-Based Routing, Multipath Routing, Non-Cooperation, Selfish Network, Traffic Assignment.

I. Introduction

Multipath routing, in which more than one path is used to transmit data for the same source-destination (SD) pair, has been studied in both wired and wireless networks. In this paper, we focus on the approach that traffic is scheduled to be transmitted among all its available paths such that the system cost is minimized [10], [14].

Most of the existing work assumes that all nodes in the network are cooperative and comply with the prescribed protocols. However, this is not a reasonable assumption in networks with selfish nodes, which are only interested in maximizing their own "utilities". Selfish nodes may not be willing to forward packets for others' flows because of the limited resources. They tend to drop data packets of other nodes either completely or selectively so as to reduce their energy consumptions or save transmission resources. The performance of the network as a whole is adversely affected by these nodes [12]. Examples of selfish networks include ad hoc networks [2] and inter-domain networks [1]. Several routing protocols have been proposed aiming at providing incentives for selfish nodes to cooperate. These incentives are either based on reputation or monetary transfer.

In a monetary transfer system, payments are used to encourage selfish nodes to cooperate [5], [21]. The critical issue in this system is to determine the proper transmission payment. Payment schemes of single path routing with energy constraints have been excessively studied [2], [7], [19]. Some other studies take the selfish behaviours of autonomous systems (ASs), operated by different service providers, into consideration in inter-domain networks [1], [4], [16].

Among the studies on selfish networks, there is little work studying multipath routing. The optimal, strategy-proof scheme for multipath traffic assignment (OSMA) was proposed in [18] to allocate bandwidth. Since OSMA takes only one request at a time, it is not optimal and strategy-proof (see the definition in Section II) for multiple requests. Based on OSMA, two algorithms for linear and non-linear routing prices were derived in [9]. In [17], the general second price auction was introduced to alleviate overpayment of multipath routing in selfish networks. However, this scheme may result in cheating and routing inefficiency.

In this paper, a general model for multipath routing in selfish wired networks is proposed. We adopt the Vickrey-Clarke-Groves (VCG) auction of the procurement problem to design an optimal auction-based multipath routing (OAMR) scheme for selfish networks in order to provide incentives for selfish nodes to carry flows for other nodes. Moreover, we propose the sequential auction-based multipath routing (SAMR) scheme with different sequencing strategies as an approximation to OAMR to reduce the computational time. Finally, OAMR and SAMR are implemented with a batching-based method which allocates bandwidth to all routing requests arriving in a certain batching period simultaneously. In our evaluation, we find OAMR or SAMR can result in lower system cost or lower payment-cost ratio, compared to existing schemes.

The rest of the paper is organized as follows. In Section II, technical preliminaries are introduced. In Section III, we model the problem of multipath routing in selfish wired networks. In Section IV, we present and analyze OAMR. As a scalable and approximate solution to OAMR, SAMR is proposed in Section V. Section VI exhibits and discusses the simulation results. We conclude with suggestions for future research in Section VII.

II. Technical Preliminaries

We first review some concepts from auction theory. Generally, there are three parties for an auction, namely, auctioneer,

bidders, and customers. The auctioneer represents customers to conduct the auction. If the customers are procurers, the bidders in the auction are suppliers. If the customers are sellers, the bidders are consumers. In the following, in the first two auctions, the customers are procurers. The customers are sellers in the third auction.

In a general model of procurement auction [6], [8], we have an auctioneer, n suppliers as bidders, and m procurers participating in an auction to allocate divisible goods to meet a set of procurer demands. All bidders attempt to maximize their utilities while the auctioneer wants to minimize the total cost of satisfying all demands.

The VCG auction [8] is designed to motivate the bidders to truthfully report their private information to the auctioneer. The VCG auction is incentive-compatible (IC), i.e., telling the truth is the dominant strategy for any player. Another important property of the VCG auction is individual rationality (IR), which means that joining the game is always better than non-participation. An auction which is both IC and IR is said to be strategy-proof.

Ausubel clinching auction [3] is designed to auction off g divisible goods to n consumers. The price $q(t) = t$ increases gradually from $q(0) = 0$ until the market clears, i.e., the supplies meet the demands. It can be shown [3] that an Ausubel clinching auction converges to the VCG outcome.

III. A MODEL OF MULTIPATH ROUTING IN SELFISH NETWORKS

Assume that there is a directed wired network $N = (V, E)$. $V = \{v_1, v_2, \ldots, v_n\}$ is the set of n nodes, and $E = \bigcup_{k=1}^{n} E_k$ is the set of communication links, where $E_k = \{e_{k1}, e_{k2}, \ldots, e_{kd_k}\}$ consists of d_k directed links that are originated from Node v_k to the nodes in the neighbouring node set $V_k = \{v_{k1}, v_{k2}, \ldots, v_{kd_k}\} \in V$. Each link $e_{kl} \in E_k$ from Node $v_k \in V$ has a capacity C_{kl} for transmitting data to the neighbouring node $v_{kl} \in V_k$ of v_k.

A set of R SD pairs is represented as $S = \{s_1, s_2, \ldots, s_R\}$. These SD pairs request bandwidth in the form of a request vector $\{q_1, q_2, \ldots, q_R\}$. For each SD pair s_i, there exists a set of node-disjoint paths [10], [14] $\mathcal{P}_i = \{P_i^1, \ldots, P_i^{m_i}\}$ where $m_i \geq 2$. When this condition is not met (i.e. $m_i = 1$), unipath routing is applied in selfish networks [2], [7], [19]. Each link e_{kl} originated from an intermediate node v_k has a marginal cost function $f_{kl}(x)$ and the current available bandwidth b_{kl} (where $0 \leq b_{kl} \leq C_{kl}$), which are both private information and only known to Node v_k. $f_{kl}(x)$ is an increasing function, and represents the cost of forwarding one additional unit of traffic when x units of bandwidth has been allocated. Indeed, the higher the traffic load on a link, the longer the queueing delay or the higher the packet dropping probability. The cost for Node v_k to carry a flow requiring y_{kl} units of bandwidth on Link e_{kl}, where $y_{kl} \leq b_{kl}$, is $c_{kl}(y_{kl}) = \int_{C_{kl}-b_{kl}}^{C_{kl}-b_{kl}+y_{kl}} f_{kl}(x)dx$.

Suppose that Node v_k reports $\hat{\mathbf{f}}_k = (\hat{f}_{kl}(x)|l = 1, \ldots, d_k)$ and $\hat{\mathbf{b}}_k = (\hat{b}_{kl}|l = 1, \ldots, d_k)$ instead of $\mathbf{f}_k =$

$(f_{kl}(x)|l = 1, \ldots, d_k)$ and $\mathbf{b}_k = (b_{kl}|l = 1, \ldots, d_k)$, respectively. Here, Node v_k cheats when $\mathbf{f}_k \neq \hat{\mathbf{f}}_k$ or $\mathbf{b}_k \neq \hat{\mathbf{b}}_k$. The source node of an SD pair must pay for the intermediate nodes to carry its flows, and this payment must at least cover the forwarding costs of the intermediate nodes. Let p_k be the total revenue received by Node v_k in forwarding traffic from other nodes with the bandwidth allocation on E_k as $\mathbf{y}_k = (y_{kl}|l = 1, \ldots, d_k)$. Let $c_k(\mathbf{y}_k) = \sum_{l=1}^{d_j} c_{kl}(y_{kl})$ be the forwarding cost of Node v_k. We assume that all nodes in the network are selfish. A selfish node v_k aims to maximize its utility, u_k, where

$$u_k = p_k - c_k(\mathbf{y}_k) \tag{1}$$

IV. OPTIMAL AUCTION-BASED MULTIPATH ROUTING (OAMR)

In this section, we propose a routing algorithm OAMR to handle the bandwidth allocation in selfish networks. OAMR is implemented in a batching-based manner in which requests arriving in a certain batching period are handled at the end of the batching period simultaneously.

A. Analogy

We attempt to use the procurement auction to solve the multipath routing problem in selfish networks. In our analogy (see Table I), bandwidths from links on the transmission paths of the flows are auctioned off to meet the communication requests of the SD pairs. The source nodes of these SD pairs make certain payments to the intermediate nodes with these links such that selfish nodes can be cooperative.

TABLE I
ANALOGY OF MULTIPATH ROUTING AND PROCUREMENT AUCTION

Multipath Routing	Procurement Auction
Control centre	Auctioneer
SD pair	Procurer
Intermediate node	Bidder (Supplier)
Bandwidth	Goods
Available bandwidths of links	Supply of goods
Bandwidth request of SD pair	Demand of goods

B. Traffic Assignment and Payment Scheme

Assume that there are R incoming requests in a certain batching period. Let vector $\mathbf{x}_i = (x_{ij}|j = 1, \ldots, m_i)$ be the set of the allocated bandwidths among $\mathcal{P}_i$. The traffic assignment problem (TAP) can be formulated to minimize the total system cost, subject to the capacity and demand constraints as follows:

$$\min W = \sum_{k=1}^{n} \sum_{l=1}^{d_k} \hat{c}_{kl}(y_{kl}) \tag{2}$$

$s.t.\ y_{kl} \leq \hat{b}_{kl}\ (k = 1, 2, \ldots, n)$ (Capacity Constraints) (3)

$$\sum_{j=1}^{m_i} x_{ij} = q_i\ (i = 1, 2, \ldots, R) \text{ (Demand Constraints)} \tag{4}$$

$$y_{kl} = \sum_{i=1}^{R} \sum_{j=1}^{m_i} \delta_{kl}^{ij} x_{ij} \tag{5}$$

where

$$\delta_{kl}^{ij} = \begin{cases} 1, & \text{if } e_{kl} \text{ of } v_k \text{ is on } P_i^j \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

$$\hat{c}_{kl}(y_{kl}) = \int_{C_{kl}-\hat{b}_{kl}}^{C_{kl}-\hat{b}_{kl}+y_{kl}} \hat{f}_{kl}(x) dx \tag{7}$$

We adopt a VCG auction of procurement to design the payment scheme such that truthful reporting is the dominant strategy for selfish nodes. The total revenue received for all traffic relayed by Node v_h is p_h^*, given by:

$$p_h^* = W_{-h}^* - W^* + \hat{c}_h(\mathbf{y}_h^*) \tag{8}$$

where $\mathbf{y}_h^*$ is the optimal bandwidth allocation vector for a selfish node v_h, W^* is the optimal system cost of TAP, and W_{-h}^* is the minimized system cost of TAP without Node v_h. The source node of a flow makes payment to Node v_h proportional to the portion of traffic load traversing that node. The source node of SD Pair s_i should pay p_h^i to Node v_h, where $p_h^i = p_h^* \frac{\sum_{j=1}^{m_i} \sum_{l=1}^{d_h} \delta_{hl}^{ij} x_{ij}}{\sum_{l=1}^{d_h} y_{hl}^*}$.

The following theorem shows that, with this payment scheme, each selfish node will report its truthful information, i.e., $\hat{\mathbf{c}}_k = \mathbf{c}_k$ and $\hat{\mathbf{b}}_k = \mathbf{b}_k$, where $\hat{\mathbf{c}}_k = (\hat{c}_{kl}|l = 1, \ldots, d_k)$.

Theorem 1: If OAMR is used, truthful reporting is the dominant strategy for each node, irrespective of the bids of other nodes.

It can be proved that the utility of any node in the network is maximized when the selfish node reports truthfully. The proof can be found in [22].

Since $u_k \geq 0$ for any selfish node v_k, this encourages selfish nodes to join the transmission, resulting in a non-negative utility. Consequently, OAMR is also IR. Hence, OAMR is a strategy-proof mechanism because OAMR is both IC and IR.

C. Payment-Cost Ratio

OMAR requires the source nodes of the SD pairs to pay more than the actual costs of the selfish nodes forwarding their traffic. In this subsection, we derive the ratio of the payment to the system cost, which is defined as follows:

$$\mathcal{R} = \frac{\sum_{k=1}^{n} p_k^*}{W^*} \tag{9}$$

Theorem 2: Suppose f_{max} and f_{min} are the maximum and minimum values of any marginal cost function $f_{kl}(x)$ after and before the allocation through OAMR for any link e_{kl}, respectively. That is:

$$f_{max} = \max\{f_{kl}(C_{kl} - b_{kl} + y_{-h,kl}^*)|v_h, v_k \in V, e_{kl} \in E_k\}$$

$$f_{min} = \min\{f_{kl}(C_{kl} - b_{kl})|v_k \in V, e_{kl} \in E_k\} \tag{10}$$

where $\mathbf{y}_{-h,k}^* = (y_{-h,kl}^*|e_{kl} \in E_k)$ is the optimal allocation minimizing the system cost among $V \setminus \{v_h\}$ with respect to

$\mathbf{c}_{-h}$. The payment-cost ratio $\mathcal{R}$ is bounded as:

$$1 \leq \mathcal{R} \leq \frac{(n-1)f_{max}}{f_{min}} \tag{11}$$

The proof can be found in [22].

V. SEQUENTIAL AUCTION-BASED MULTIPATH ROUTING (SAMR)

OAMR needs to solve TAP $(n + 1)$ times, including one time for TAP with all network nodes and n times for TAP with the node set $V \setminus \{v_h\}$ to compute W_{-h} for any $v_h \in V$, to determine the allocation and payment scheme. Thus, the computational time of OAMR is terribly long when the network size and the number of requests are large. In this section, a sequential auction-based multipath routing scheme is proposed as an approximate algorithm to OAMR.

A. Analogy

We fist apply the sequential auction [8] to solve the multipath routing problem. In this scheme, bandwidth is auctioned off sequentially on each node along the transmission path. In each sub-auction, a request from an SD pair is satisfied subject to the capacity constraints, and a new analogy between the procurement auction and multipath routing can be made. Compared with the previous analogy in Table I, the procurement auction in the new analogy consists of one auctioneer, several bidders, and only one procurer. The auctioneer needs to determine an efficient assignment to meet the procurer's demand. Furthermore, all nodes on a transmission path available for the SD pair are grouped as a bidder to participate in such sub-auction. Therefore, the available bandwidth of the path is viewed as the supply offered by the bidder.

B. Water-Draining Algorithm

We develop Algorithm 1, which finds a VCG outcome for a single request in a sub-auction of SAMR so as to reduce the computational time with reference to the Ausubel auction.

In each sub-auction in SAMR, a single routing request requiring q units of bandwidth is allocated. As is mentioned in our model, a set of node-disjoint paths, $\mathcal{P} = \{P^1, \ldots, P^m\}$, is available for the SD pair. Each intermediate node v_k on these paths reports its marginal cost function vector of the outgoing links $\hat{\mathbf{f}}_k$, and the corresponding available bandwidth vector $\hat{\mathbf{b}}_k$.

Algorithm 1 computes the bandwidth allocation problem in a water-draining style such that the price is gradually lowered from the highest price. In Lines 19 - 24 of Algorithm 1, a certain amount of bandwidth from the set of paths in SP is clinched at the current price p_b, and then the accumulated payments of the clinched bandwidths to paths via the Ausubel clinching auction is calculated. In Line 21, the cumulative payment to an active path in SP is calculated when the price lowers from p_u to p_b. The intuition is to add up all payments for additional clinched bandwidths at each price. The clinched amount $ch_j(\eta)$ at price $\eta \in [p_b, p_u]$ from P^j is the additional bandwidth required to meet the bandwidth requirement without P^j so that the payment of the increased

clinched bandwidth $d(ch_j(\eta))$ from Path P^j is maximized. At the end of this step, the price is lowered to p_b and the total clinched bandwidth from P^j is $x_j = q - y_{-j}(p_b)$ as in Line 22. Finally, when the algorithm stops, the vector x converges to the optimal assignment for q and p' corresponds to the payment (See Theorems 3-4). The computational complexity of Algorithm 1 is $O((M+1)\Gamma\log(\frac{1}{\epsilon}))$, where M is the maximum number of available paths for an SD pair, ϵ is the error bound, and Γ is the computational complexity of computing the function values (i.e. $F_j^{-1}(x)$) at a given price.

Algorithm 1: Water-Draining (WD) Algorithm

Input: Available path set $\mathcal{P} = \{P^1, P^2, \ldots, P^m\}$, marginal cost functions $\hat{\mathbf{f}}_k$, available bandwidth $\hat{\mathbf{b}}_k$, and bandwidth requirement q

Output: Traffic assignment $\mathbf{x} = (x_1, x_2, \ldots, x_m)$ among path set P, and a set of cumulative payments to the paths $\mathbf{p}' = (p'_1, \ldots, p'_m)$

1 **begin**
2   Initialize: SP$\leftarrow \mathcal{P}$, WP$\leftarrow \emptyset$, $p_u \leftarrow \infty$;
3    $\mathbf{x} = \mathbf{0}$ and $\mathbf{p}' = \mathbf{0}$, where $\mathbf{0}$ is zero vector;
4    $\forall P^j \in \mathcal{P}$, define $F_j(x) = \sum_{e_{kl} \in P^j} \hat{f}_{kl}(C_{kl} - \hat{b}_{kl} + x)$ as the marginal cost of Path P^j, and $B_j = min\{\hat{b}_{kl} | e_{kl} \in P^j\}$ as the available bandwidth of Path P^j;
5   **while** $q < \sum_{j=0}^m x_j$ **do**
6   **if** $SP \neq \emptyset$ **then**
7        $z = argmax_{P^j \in SP}(F_j(0))$;
8        $p_b = F_z(0)$;
9   Move P^z from SP to WP;
10   **else**
11   Network cannot support the request;
12   STOP;
13   **end**
14   **for** each path P^j **do**
15   **if** $\sum_{P^j \in SP} F_j^{-1}(p_b) < q$ **then**
16   Use bisection method to find $p_b \leq \varphi \leq p_u$ such that $\sum_{P^j \in SP} F_j^{-1}(\varphi) = q$ and $x_j \leq B_j \; \forall P^j$;
17          $p_b = \varphi$;
18   **end**
19   **if** $P^j \in SP$ **then**
20   //Ausubel auction within price interval $\eta \in [p_b, p_u]$
21          $p'_j = p'_j + \int_{p_b}^{p_u} \eta \; d(ch_j(\eta)) = p'_j + \int_{p_b}^{p_u} \eta \cdot ch'_j(\eta) d\eta$, where $p_b \leq p_u$, $ch_j(\eta) = min\{y_{-j}(\eta) - q, 0\}$, $y_{-j}(\eta) = \sum_{P^h \in \mathcal{P}, P^h \neq P^j} y_h(\eta)$, and $y_j(\eta) = F_j^{-1}(\eta)$;
22          $x_j = max\{q - y_{-j}(p_b), 0\}$;
23          $p_u = p_b$;
24   **end**
25   **end**
26   **end**
27 **end**

Theorem 3: SAMR achieves the most efficient traffic assignment when it needs to handle just one request.

Theorem 4: The payments of Algorithm 1 converge to the payments in VCG auction whose bidders are paths when it needs to handle just one request.

Interested readers can refer to [22] for the proofs.

With the WD algorithm, the payment made by the source node of an SD pair to its available paths, which act as bidders in the sub-auction, is calculated. Then, the payment to any $v_h \in P^j$ can be derived from the path payment p'_j such that:

$$p_h = p'_j - \sum_{\substack{a_{kl} \in P^j \\ k \neq h}} \hat{c}_{kl}(x_j^*) \tag{12}$$

where $\hat{c}_{kl}(x_j^*)$ is the reported cost of x_j^* units of bandwidth of Link a_{kl} on Path P^j. If a node is not on any path in $\mathcal{P}$, it will not receive any payment from the SD pair.

Intuitively, the system costs without Node v_h and without Path j are equal for any $v_h \in P^j$. Theorem 5 can be derived.

Theorem 5: If there is only one request needed to be handled, truthful reporting is a dominant strategy.

The proof can be found in [22].

C. Sequencing Strategies

The WD algorithm can only handle a single request and guarantee truthfulness and optimality for this case. When it is necessary to handle R requests with bandwidth demand vector $\{q_i | i = 1, \ldots, R\}$, the requests must be handled sequentially. As a result, the ordering of the requests is crucial to the performance of SAMR when dealing with multiple requests. Here, we consider three basic sequencing strategies:

1) Large Request First (LRF): With this strategy, the request with the largest bandwidth requirement among all outstanding requests is handled first by the WD algorithm.

2) Small Request First (SRF): With this strategy, the request with the smallest bandwidth requirement among all outstanding requests is handled first by the WD algorithm.

3) Fixed Amount in Turns (FAIT): With this strategy, requests are auctioned off in turns. In each turn, the maximum auctioned bandwidth is capped at Δ units. The auction is repeated until all requests are satisfied.

VI. PERFORMANCE EVALUATION

We evaluate the routing schemes using a simulation program in C++. We simulate a real backbone network called Abilene which has 11 nodes and 28 directed links with capacity $C = 10$ Gbps [20]. Two different link cost functions, namely $ln(\frac{C}{C-x})$ [18] and $\frac{1}{C-x}$ [11] are used in the evaluation.

For a routing request, the source and destination nodes of SD pairs are randomly selected from the set of network nodes. The duration time follows a lognormal distribution whose mean is 54 seconds [15]. The bandwidth requirement follows a lognormal distribution with mean 187.5 Mbps [13]. The interarrival time between two successive requests follows the exponential distribution with arrival rate λ which can be 5/s, 5.5/s, 6/s, 6.5/s, and 7/s.

In the simulation, we evaluate Unipath routing [2], [19], OSMA [18], OAMR, SAMR-LRF, SAMR-SRF, SAMR-FAIT-50, SAMR-FAIT-100, and SAMR-FAIT-150 where SAMR-FAIT-w is the SAMR using the FAIT strategy with $\Delta = w$.

Our batching-based algorithms are implemented in a centralized fashion in which the control centre in the network collects the routing requests so that bandwidths are reserved for them with corresponding payments determined by OAMR or SAMR. (See the details of the implementation in [22].)

In the evaluation, three batching periods with T = 5, 10, and 15 seconds are considered. The algorithms are compared in terms of the following metrics:

1) *System cost:* The sum of flow-induced costs at the participant nodes is called the system cost or forwarding cost of the routing request.

2) *Payment-cost ratio:* The payment-cost ratio of a routing request is defined as the total payment over the system cost. Here, the total payment of a routing request is the sum of the payments to intermediate nodes.

3) *Setup time:* The setup time of a routing request is the period from when the request is sent to the control centre to when the bandwidth allocation result is received by the source node.

Due to space limitations, we only show the major results and conclusions of the simulation in the following. Interested readers can refer to [22] for details.
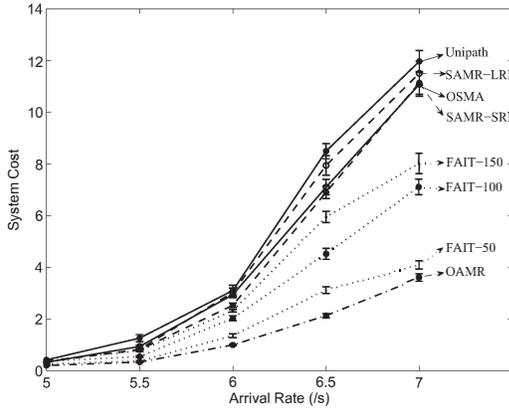
A. System Cost

Fig. 1.   Comparison of system cost of different algorithms.

Fig. 1 shows the system costs of different algorithms when the batching period is 5 seconds and link cost function is $\frac{1}{C-x}$. Among all algorithms, multipath algorithms always have lower system costs than that of unipath routing. Compared with other multipath routing schemes, SAMR-LRF and OSMA have relatively high system costs. Since SAMR-SRF handles the smaller requests first and the later larger ones are better satisfied with lower system cost, the system cost of SAMR-SRF is smaller than SAMR-LRF. SAMR equipped with FAIT can achieve relatively low system cost among all algorithms, since in FAIT the maximum satisfied request is restricted at Δ so that the bandwidth can be allocated more uniformly. Therefore, smaller Δ of FAIT will result in smaller system cost. As shown in Fig. 1, FAIT-50 is the closest to OAMR

which is the optimal scheme requiring long computational time. Theoretically, if Δ is small enough, FAIT-Δ can infinitely approximate the optimal one.

The results in other cases with different batching periods and link cost functions are similar. SAMR-FAIT can always achieve the lowest system cost among all practical algorithms.

B. Payment-Cost Ratio

It is expected that the intermediate nodes can be cooperative with lower payment-cost ratio. Fig. 2 shows that the payment-cost ratios for the case with a batching period of 5 seconds and link cost function of $\frac{1}{C-x}$. Among these algorithms, the batching-based algorithms can alleviate the overpayment [7], while the payment cost ratios of OSMA and Unipath grow dramatically with the increase of the arrival rate. When the arrival rate is small, the payment-cost ratio of unipath routing is the lowest, because the number of participant nodes in unipath routing for a routing request is less than that of multipath routing and the total payment is smaller. According to Theorem 2, when the arrival rate increases, the difference between f_{max} and f_{min} becomes larger so that the payment-cost ratio increases. SAMR-based algorithms distribute the flows into the network more uniformly. As a result, SAMR-based algorithms have lower payment cost ratios. SAMR-FAIT can achieve the lowest payment-cost ratio.
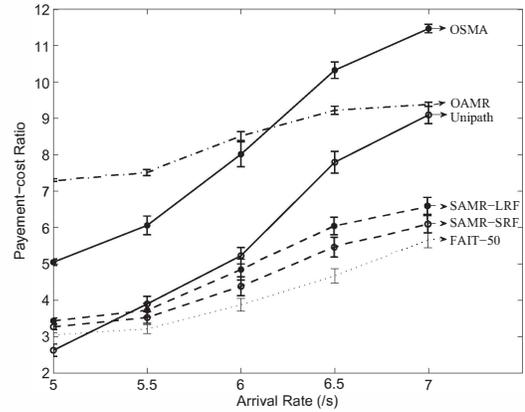

Fig. 2.   Comparison of payment-cost ratio of different algorithms

Smaller Δ in FAIT results in smaller payment-cost ratio, since the maximum auctioned bandwidth is limited and the payments of this auctioned bandwidth are reduced. The trends of other cases are similar. SAMR-FAIT-50 can always achieve the lowest payment-cost ratio.

C. Setup Time

Different from unipath routing and OSMA in which the unmet requests are dropped, our batching-based algorithms delayed the unmet requests to the next batching period until the requests are satisfied. As a result, the blocking probability is zero in our schemes. In Fig. 3, the setup time of SAMR-based
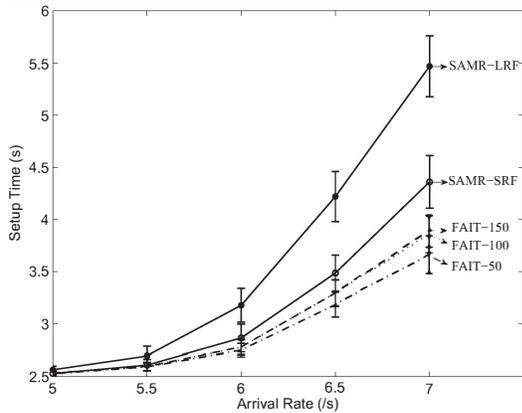
Fig. 3.   Comparison of system cost of different algorithms.

algorithms for the case with a batching period of 5 seconds and a link cost function of $\frac{1}{C-x}$ is illustrated.

When the arrival rate is low, the setup time is about half of the batching period length. The setup time rises with the increase of the arrival rate since more requests are delayed to the next batching period due to the shortage of available bandwidth. Because SAMR-FAIT-50 can allocate the bandwidth more uniformly (so that more requests are met in the current batching period), it has the lowest setup time among all illustrated algorithms. It can be found that with the decrease of Δ in FAIT, the setup time of SAMR-FAIT can be reduced.

In our schemes, there is a tradeoff between setup time and system cost and payment-cost ratio. A setup time of around three seconds is acceptable to certain applications of data transmission. Furthermore, compared with zero blocking probabilities in our SAMR routing schemes, unipath routing and OSMA have blocking probabilities of 9.69% and 6.89%, respectively, when the arrival rate is six requests per second.

VII. CONCLUSIONS AND FUTURE WORK

We have constructed an analytical model to analyze OAMR, and SAMR with different sequencing strategies. OAMR can guarantee truthfulness and efficiency of selfish nodes for multiple requests, while SAMR is truth-telling and efficient only for the case of a single request. However, SAMR can dramatically reduce the computational time with only a small sacrifice in the system cost. The distributed version of SAMR can be devised so as to further improve the scalability of the allocation mechanism. The proposed scheme can be extended to work in the wireless environment.

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