Jointly Effective Optimal Flow Control and Multi-path Routing for Wireless Networks under Probabilistic Attacks

Xiaomei Zhang

Abstract—A wireless network is vulnerable to jamming attacks since the network relies on open and shared wireless channels. Maintaining an acceptable level of network performance degradation has been an important problem in the wireless network. This paper studies a scheme for network performance optimization by exploiting dynamic rate control and multi-path routing in the wireless network under probabilistic jamming. We model the optimization problem through maximizing the network utility associated with the effective data flows and propose an effective optimal flow control (EOFC) approach to allocate resource on multiple paths considering the effect of jamming. A novel distributed algorithm is designed to adjust flow rates adaptively on each path using multi-path routing. Our simulation results demonstrate that higher effective network throughput and better fairness can be achieved under jamming by our EOFC algorithm than the standard OFC.

Keywords—routing; flow control; jamming; wireless networks

1. INTRODUCTION

Due to the fundamental characteristic of wireless medium, a wireless network is vulnerable to interference, failure and malicious attacks. Jamming or Denial-of-Service is one of the most effective attacks against the wireless network. DoS attacks can influence data communication by sending high transmission power signals[1]. The attackers in [2][3] corrupt users' transmission by sending jamming packets incorporating wireless medium access control (MAC) protocol information into attacks. Other jamming attackers exploit the structure of wireless cross-layer protocol to perform efficient attacks, requiring less energy by targeting certain link layer and MAC implementations, routing protocol or the transport layer SYN message flooding[4]. An important problem in the design of a wireless network is to maintain the network performance in presence of jamming attacks.

When jamming occurs, the network performance degrades since the jammer who competes with users for the network channel resource has a direct impact on wireless links. Multi-path routing, which can be an useful anti-jamming technique to improve the network performance, has been actively studied in a communication network under jamming attacks[5][6][7]. However, how to utilize multi-path routing to maintain an acceptable level of network performance degradation is still a crucial issue for the wireless network under jamming. In this paper, we are interested in the problem of optimizing the total network performance of multi-path flows over a wireless network in the presence of jamming.

In order to make efficient utilization of multi-path routing, the wireless network must be able to provide a better traffic management among multiple routing paths between source and destination. Optimal Flow Control (OFC) approach[8], which is regarded as one of the most successful solutions for this problem, formulates flow control as an optimization problem and then maximizes the aggregate utility. When a jammer is present in the wireless network, wireless links are typically lossy and the packet loss ratio is often order higher, due to jamming packets sent by the attacker to contend for the wireless channel. The effective data rate received successfully at the destination node is lower than the transmission rate at the source. In this paper, we generalize the OFC approach to obtain new problem formulations, namely effective optimal flow control (EOFC), which uses the effective utility associated with the effective data rate and considers the potential effect of jamming on data flows.

To mitigate the impact of jamming attacks, the authors of [5] design the restoration strategies dynamically adjusting traffic routes and channel assignment in response to jamming. By only classifying each wireless node as either jammed or not jammed to reroute around jammed regions, this method does not provide sufficient protection from mobile attacks and dynamic strategies by jammers. Mustafa et.al[6] propose a multipath selection with the goal of improving jamming resilience in the wireless network. However, it only considers multi-path routing rather than joint multi-path routing and flow control when multiple paths are available. Tague et.al[7] study the problem of throughput optimization in multipath routing in the presence of jammers using portfolio selection theory from finance. However, the objective function in their model is a specific utility function rather than a general utility function. Moreover, instead of using congestion constraint in [7], we are interested in the optimization problem with a new constraint which could more accurately reflect the characteristic of contention-based MAC protocols.

Due to the uncertainty in the attacker's location and jamming strategy, the effect of jamming can be characterized as probabilistic. The packet loss ratio on each wireless link is modeled as a random variable. Under the lossy flow model, we examine the utility function corresponding to the effective flow received at the destination node and explore effective optimal flow control under probabilistic jamming. In this paper, the joint multi-path routing and effective flow control...
problem is formulated as a constrained optimization problem which takes account of medium access control protocols in the wireless network. We further solve this problem to develop a novel distributed flow control algorithm to obtain the optimal effective rate allocation on multiple wireless paths. Our numerical results corroborate that the network performance is enhanced by achieving higher effective throughput and better fairness among effective flow rates by the EOFC algorithm than the standard OFC.

2. SYSTEM MODEL

A. Network Model

We consider a wireless network represented by a directed graph G(V,E), where V is the set of nodes and E is the set of links. We denote a link as a pair of nodes (i,j), where i is the transmitter of the link and j is the receiver. Let a subset S be the set of sources and C be the set of fixed data rate in E. Each source has multiple available paths or routes from the source to destination. We let a set S(i,j) be the set of sources whose flows traverse through link(i,j). The set of all the available paths of source s is defined by Rs=[Rs,1,Rs,2,...,Rs,ks].

Denote the vector As(i,j) as the set of flow s' paths pass through link(i,j), whose nth element is equal to 1 if the path Rs,n of flow s contains link (i,j) and 0 otherwise. Each path Rs,n is given by a subset pl in the network and L is the size of pl. For each source s, let x(s,n) be the rate of source s on the path Rs,n and xs be the total source rate. Let Xs=[xs,1,xs,2,...,xs,ks] and X=[X 1,X2,...,Xs] be the path rate vectors of source s and all sources.

The wireless nodes operate with a single wireless channel and adopt a random access control protocol. We define Nout(i) as the set of nodes whose transmissions cause interference to the receiver of link (i,j), excluding node i, and Ncom(i) as the set of links whose transmissions get interfered from the transmitter of node i, excluding outgoing links from node j. Denote Nconf(i) as the set of nodes to which node i is transmitting packets and Nrec(i) as the set of nodes from which node i receives packets. We assume that each node has a contention resolution protocol of the persistence transmission. Node i transmits data on link (i,j) with a persistence probability Pr(i,j).

B. Attacker Model

We consider the adversary inserts attackers into the wireless network. The network has no information about the jamming strategy, the relative location and mobility patterns, etc. We assume that packet loss occurs only due to jamming attacks rather than congestion which can be managed by the provision of the underlying network protocols. In presence of jamming, the increased probability of collision usually leads to increased packet loss ratio of each wireless link for the persistence transmission mechanism.

As the adversaries’ actions are unknown and uncertain to the network, the impact of jamming is probabilistic from the perspective of the network. The ratio of packets successfully transmitted over each wireless link can be formulated as a random variable using statistics from nodes. Due to the packet loss in wireless links, the data rate of a flow becomes thinner and thinner along its routing path, and the effective throughput received at the destination node is lower than the throughput at the source node. We jointly optimize flow control and routing over multiple paths based on the characterization of statistics due to the impact of jamming attacks.

3. THE OPTIMAL FLOW CONTROL APPROACH

We first study the routing and optimal flow control problem in the wireless multi-path network when there is no jamming. We use the contention resolution method based on the transmission persistence probability at the MAC layer, node i of link (i,j) transmits packets with a persistence probability Pr(i,j) to contend the channel. Node i uses the persistence probability Pr(i,j) to contend for all available channel resource[9]. We impose the MAC resource constraint that the total flow rate over link (i,j) should be no more than the average capacity.

The cross-layer rate optimization across the transport layer and the MAC layer can be formulated as the network utility maximization (NUM) with the constraints come from MAC protocol and multi-path routing. The objective of optimal flow control is to choose the rates X so as to maximize the total utility subject to the constraints:

\[
\text{Problem: max } \sum_{s \in S} \sum_{n=1}^{L} \log \left( x_{s,n} \right) \text{ s.t. : } \sum_{s \in S(i,j)} A_{s,i,j} X_s \leq c(i,j) \prod_{d \in N_{com}(i,j)} (1 - P_d) \]

\[
x_{s,n}^{\text{min}} \leq x_{s,n} \leq x_{s,n}^{\text{max}}
\]

\[
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\]

The utility function Us is assumed to be [10]:

\[
U_s(x_s) = \begin{cases} 
\log x_s & \text{if } \alpha = 1 \\
(1 - \alpha)^{-\frac{1}{1-\alpha}} - \alpha x_s & \text{if } \alpha \geq 0, \alpha \neq 1
\end{cases}
\]

Appealing to the Lagrangian dual method, a dual algorithm for the updates of source rates and link prices is given by:

4. EFFECTIVE UTILITY-OPTIMAL FLOW CONTROL APPROACH UNDER PROBABILISTIC JAMMING

A. Optimization Constraints

In our wireless network, when jamming attacks happen, the ratios of packet loss on wireless links decline due to the increased percentage of incurred collisions of data packets

\[g_{s,n} = \prod_{(i,j) \in R_{s,n}} h_{i,j} \]
transmissions. We define the ratio of packets successfully delivered over link \((i,j)\) as \(s_{i,j}\) which be characterized as a random variable due to the uncertainty in the impact of jamming. In traversing the path \(R_{s,n}\), the effective flow rate of source \(s\) is reduced at the destination node. The end-to-end packet success ratio for path can be formulated as

\[
\sum q_{i,j}^{(i)} = s \in S((i,j)) \cap R_{s,n} \cap R_{s} ((i,j)) \cap R_{s} \tag{6}
\]

where

B. EFOC Approach with Multi-path Routing

At the destination node of flow \(s\), the correctly received data rate can be described as effective rate. Each flows has a utility function associated with the effective rate. Our principle objective is to maximize the overall effective network utility of all flows:

\[
\text{Problem:} \quad \max \sum_{s \in S} \left(U_s \left(\sum_{n=1}^{N_s} \theta_{s,n} x_{s,n} \right)\right)
\]

\[
\text{s.t.:} \quad \sum_{Q_s} g_{s,n}^{(i)} x_{s,n} \leq c_{i,j}^{(i)} p_{(i,j)} \prod_{d \in N_{i}} (1 - P_d)
\]

\[
x_{s} \leq \frac{k_s}{\sum_{n=1}^{N_s} x_{s,n}} \leq x_{s}^{\text{max}}
\]

\[
0 \leq P_t \leq 1
\]

We use a change of variables. This formulation turns into the following convex programming:

\[
\text{Problem:} \quad \max \sum_{s \in S} \left(U_s \left(\sum_{n=1}^{N_s} \theta_{s,n} x_{s,n} \right)\right)
\]

\[
\text{s.t.:} \quad \log \sum_{Q_s} g_{s,n}^{(i)} e^{x_{s,n}} - \log c_{i,j}^{(i)} - \log p_{(i,j)}
\]

\[
- \log_{d \in N_{i}} (1 - P_d) \leq 0
\]

\[
x_{s} \leq \frac{k_s}{\sum_{n=1}^{N_s} e^{x_{s,n}}} \leq x_{s}^{\text{max}}
\]

\[
0 \leq P_t \leq 1
\]

Note that the utility function is strictly concave [11]. The Lagrangian function is given by Equation (9):

\[
L(\tilde{X}, f, \lambda, \tilde{\lambda}) = \sum_{s \in S} \left(U_s \left(\sum_{n=1}^{N_s} \theta_{s,n} e^{\tilde{X}_{s,n}} \right)\right)
\]

\[
+ \tilde{\lambda}(x_{s}^{\text{max}} - \sum_{n=1}^{k_s} e^{\tilde{X}_{s,n}} - \tilde{\Delta}(x_{s}^{\text{min}} - \sum_{n=1}^{k_s} e^{\tilde{X}_{s,n}}))
\]

\[
- \sum_{(i,j)} \lambda_{i,j} (\log \sum_{Q_s} g_{s,n}^{(i)} e^{\tilde{X}_{s,n}}) - \log c_{i,j}^{(i)}
\]

\[
- \log p_{(i,j)} \prod_{d \in N_{i}} (1 - P_d) \right)
\]

The objective function of the dual problem is given by

Based on the Arrow-hurwicz gradient method[11, pp. 154-165], we can obtain:

\[
\min_{\lambda, \tilde{\lambda}} D(\lambda, \tilde{\lambda}) = \max_{\tilde{f}, \tilde{\Delta}} L(\tilde{X}, f, \lambda, \tilde{\lambda}) \tag{13}
\]

\[
D(\lambda, \tilde{\lambda}) = \max_{\tilde{f}, \tilde{\Delta}} L(\tilde{X}, f, \lambda, \tilde{\lambda}) \tag{10}
\]

We have the Lagrangian multipliers for the dual by the gradient method as follows:

\[
\lambda_{(i,j)}(t + 1) = [\lambda_{(i,j)}(t) - \gamma \left( \sum_{d \in N_{i}} \log(1 - P_d(t)) \right)
\]

\[
+ \log p_{(i,j)}(t) + \log c_{i,j}^{(i)} - \log \left( \sum_{Q_s} g_{s,n}^{(i)} e^{\tilde{X}_{s,n}(t)} \right)]^+ \tag{14}
\]

\[
\tilde{\lambda}(t + 1) = [\tilde{\lambda}(t) + \gamma \left( x_{s}^{\text{max}} - \sum_{n=1}^{k_s} e^{\tilde{X}_{s,n}(t)} \right)]^+ \tag{15}
\]

\[
\Delta_{(i,j)}(t + 1) = [\Delta_{(i,j)}(t) - \gamma \left( x_{s}^{\text{min}} - \sum_{n=1}^{k_s} e^{\tilde{X}_{s,n}(t)} \right)]^+ \tag{16}
\]

The MAC layer problem can be solved by[9]

C. Joint EFOC and Multi-path Routing Algorithm

We propose Algorithm 1 based on the problem formulation of joint multi-path routing and EFOC. It is designed in a fully distributed manner while each update computation is only based on local information of a source or a link.

There are usually oscillations in the Lagrangian algorithm for the multi-path network. In order to improve the convergence speed and eliminate the effect of oscillates, we introduce an augmented variable \(f_{s,n}\) to the following modified objective function, which replaces the objective function of formulation (8):

\[
\max \sum_{s \in S} \left(U_s \left(\sum_{n=1}^{N_s} \theta_{s,n} x_{s,n} \right)\right) - \sum_{s \in S} \sum_{n=1}^{N_s} \frac{1}{2} \left( f_{s,n} - f_{s,n} \right)^2 \tag{18}
\]
5. PERFORMANCE EVALUATIONS

In this section, we present numerical results to demonstrate the efficiency of our solutions. Consider a wireless network given in Fig. 2 with 10 links, 9 nodes and two sources.

In the OFC approach, Fig. 3 shows the flow rates among four paths. Two path rates converge to (0.09, 0.054). They share the bottleneck node C with equal flow rate 0.054. The OFC approach provides fair rate allocation.

Under the effect of jamming attacks, the effective rates of four paths in OFC approach are depicted in Fig. 4. The effective flow rates decrease to (0.034, 0.027, 0.02, 0.028) among four paths. For EOFC, the effective rates in Algorithm 1 are shown in Fig. 5. It can be seen that EOFC yields a higher effective rates (0.087, 0.04, 0.037, 0.086) for four flows than OFC. Fig.6 clearly shows that the effective throughput of EOFC can be higher than that of OFC. We further take a closer look at rate allocation among flows and effective flows in Fig.3 and Fig.4. In Fig. 3, four flows share a fair rate allocation that x1,1 equals to x2,2 and x1,2 equals to x2,1. However, the fairness is affected due to different lossy effects on four paths by jamming. x2,2 and x2,1 are lower than x1,1 and x1,2 respectively in Fig.4. In Fig.5, the effective rates x2,2 and x1,1 in EOFC are closer to each other than those in the OFC approach. The same situation happens in x2,1 and x1,2. It could demonstrate that better fairness is attained among effective flow rates by EOFC. The source adjusts its flow rate on each path adaptively to compensate the data loss by multi-path routing in our algorithm, which takes into account the effect of jamming in utility function and constraints. It is clear that the network performance under jamming is improved both through higher effective throughput and better fairness among effective flows by our proposed algorithm.

In the simulation, we run the algorithm with the original objective function in Eq.(8). The oscillation is observed in Fig.7, which motives the modification of the objective function with the augmented variable. To prevent potential oscillations, we replace Eq. (11) by Eq.(18) in Algorithm 1. The path rates for two sources convergence to (0.087, 0.04, 0.037, 0.086) in Fig.5.
6. CONCLUSION

In this paper, we investigate the problem of rate control and multi-path routing in the wireless network under probabilistic jamming. We model the problem as a holistic optimization problem by deriving the objective function with effective flows and study the effective optimal flow control by maximizing the overall effective network utility. A distributed algorithm is developed using decomposition technique and simulated to illustrate that better performance can be achieved by EOFC than the OFC.

REFERENCES