Wireless Jamming Attacks under Dynamic Traffic Uncertainty

Yalin Evren Sagduyu*, Randall A. Berry†, and Anthony Ephremides‡

***Abstract*—We analyze the effects of dynamic packet traffic on jamming attacks in wireless networks. For random access over collision channels, the jamming problem is formulated as a non-cooperative game in which nodes choose their transmission probabilities under energy and delay constraints. We relax the standard assumption of backlogged nodes and evaluate the Nash equilibrium strategies for random arrivals, which introduces the possibility that jamming attacks fail due to empty packet queues at the transmitters. The maximum feasible throughput is derived depending on whether jammers have the queue state knowledge, or not. We also model the effects of erroneous queue state inference due to random packet traffic and incorporate the channel sensing capability before jamming. The analysis extends from one transmitter-jammer pair transmitting over a single channel at a single access point to multiple transmitters and jammers, and then to an arbitrary number of subchannels at multiple channel access points. In the resulting jamming games, we show that jammers cannot effectively increase the average energy cost and cannot decrease the feasible throughput for transmitters, if they face uncertainty on transmitter queue states. Therefore, medium access is less vulnerable to jamming attacks under increasing traffic uncertainty. This motivates the use of traffic dynamics as a defense mechanism to mitigate denial of service attacks in wireless access.**

***Index Terms*—Jamming Game; Dynamic Traffic; Denial of Service Attack; Medium Access Control; Random Access; Queue Stability; Energy; Delay.**

I. Introduction

We consider the problem of jamming attacks at the Medium Access Control (MAC) layer of wireless networks. The jamming problem has been studied for a variety of wireless network settings including 802.11 networks [1]–[3], sensor networks [4], [5], multi-hop networks [6], [7] and other general wireless network models [8]–[13]. The basic assumption in many of these models is that transmitters are *always* backlogged with packets available to transmit. Instead, we consider stochastically varying packet traffic and evaluate the effects of *traffic uncertainty* on jamming attacks. If the packet traffic varies dynamically (e.g., due to bursty sources or random channel/topology effects), the transmitter queues may be empty when a jamming attack starts, resulting in a failed attack. In distributed operation it is difficult for jammers to infer whether transmitters are backlogged or not. Therefore, it is crucial to evaluate the effectiveness of jamming attacks under dynamic traffic scenarios.

To study the conflicting interests of transmitters (with individual *selfish* performance objectives) and malicious *jammers*, we consider a model in which transmitters and jammers play a *non-cooperative game* of optimizing their individual performance objectives. We evaluate the *Nash equilibrium* strategies of the resulting games when different levels of queue state information are available to jammers.

A number of related game formulations have been studied for jamming attacks, but all under the assumption of saturated packet queues at transmitters. Random access games have been considered in [11], where transmitters and jammers balance the throughput rewards and energy costs. An information-theoretic approach has been followed in [14] to model the interactions of a transmitter-jammer pair in balancing the mutual information as the objective function. A non-cooperative game has been considered in [9] for MIMO fading channels and in [15] for MAC channels with two users in the presence of a jammer. Additional energy objectives have been introduced in [10] and [16] to jamming games based on power control with different utility functions depending on the throughput rewards and energy costs. In this context, the effects of random channels on jamming games have been analyzed in [17]. The transmission strategies for jamming games may also include randomized power selection [12].

For systems with multiple channels, frequency hopping can be used to protect against jamming; the interactions of transmitters and jammers can be formulated as a game of transmitting randomly over multiple channels [18]. In addition, jamming attacks can be also modeled as an intrusion detection problem [19]. On the other hand, the extension to multihop operation requires the joint consideration with packet forwarding as studied in [6] and [7].

The typical assumption of the previous work is that all transmitters have *uninterrupted* packet traffic to transmit. Instead, we assume *stochastically* varying packet traffic and evaluate the effects of traffic dynamics on the jamming game. We consider a general scenario as shown in Figure 1, where multiple transmitters are trying to send randomly arriving traffic to a set of channel access points, while a set of jammers attempt to interfere with these transmissions and thus deny service to the transmitting nodes.

We assume a *random access* MAC model, which would be necessary in wireless networks at some level, e.g., at the

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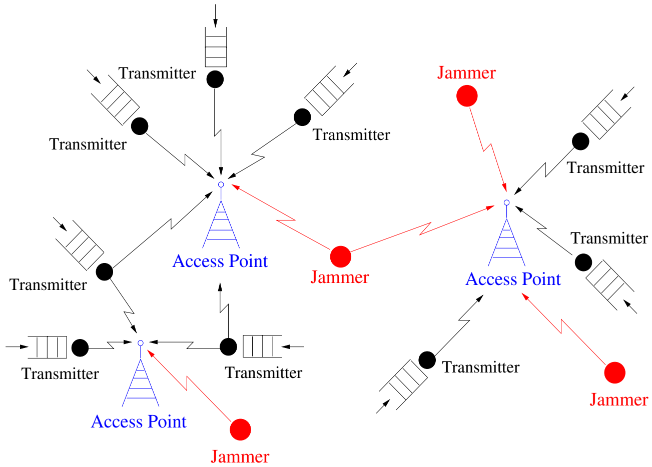

Fig. 1. Access points with transmitters and jammers.

reservation sub-channel level. Transmitters and jammers play a non-cooperative game by choosing their channel access probabilities. A transmitter's success probability depends on these access probabilities via a probabilistic capture model as in [20], [21]. The objective of each transmitter is to minimize its average energy cost subject to a target rate constraint, which is related to an average delay constraint. On the other hand, each jammer attempts to maximize the average energy costs of transmitters subject to its own average energy constraint. We consider different cases with a single or multiple transmitter-jammer pairs at a single or multiple channel access points.

For a single transmitter-jammer pair, we first evaluate the Nash equilibrium strategies depending on the availability of the transmitter's queue state information (namely, if the transmitter's queue is empty or not) at the jammer. By imposing an average energy cost on the transmitter in each case, we characterize the set of *feasible* throughput rates such that the minimum target rate (or the maximum packet delay) constraint is satisfied. We show that under increasing traffic uncertainty, the jamming attack is less successful in terms of maximizing the average energy cost of the transmitter. For both cases with and without queue state information at the jammer, the success of any wireless jamming attack increases with the average energy bound for the jammer and decreases with the average energy bound for the transmitter.

We extend the jamming game model to a case with *random* errors in queue state information. We assume that the jammer infers whether the transmitter has a packet to transmit or, not, but makes an error with a fixed probability due to the random nature of packet arrivals. Depending on this error probability, we show how the performance of a jamming attack varies from the case with full queue state information to the case without any queue state information.

We also study the effects of additional capability for jammers to *sense* the channel (as in Carrier Sense Multiple Access (CSMA) systems) before starting to jam the packet transmissions. This corresponds to the best jamming attack with the maximum energy cost and minimum feasible rate for the transmitter. This particular gain in jamming performance is only possible if the jammer is first sensing the channel except when it is transmitting and once it detects a packet transmission it begins jamming the channel immediately.

For all these cases, we impose a minimum target *rate* constraint on the transmitter and then relate it to a maximum packet *delay* constraint. The maximum feasible rates are then evaluated as function of the delay constraints. This metric is used to characterize the effect of the jammer in the different scenarios.

Next, we allow an *arbitrary* number of transmitters and jammers, and evaluate the effects of traffic uncertainty on the symmetric Nash equilibrium strategies. We show that the maximum feasible throughput rate decreases as the number of jammers increases. If jammers know the transmitter queue states, they can further reduce the maximum feasible rate. However, this additional queue state knowledge loses its value as the delay constraint increases.

The analysis is also extended to *multiple subchannels* from a single transmitter-jammer pair at one channel access point. Then, the problem is to allocate random transmissions over multiple subchannels under the assumption that each node can transmit over one subchannel at a time. In Nash equilibrium, both transmitter and jammer nodes transmit more frequently on channels that have higher capture probability. In particular, we show that the effect of traffic uncertainty (namely, whether the jammer node knows the queue state of the transmitter or not) on jamming attacks decreases, as the number of subchannels increases. The reason is that the transmitter has more opportunities to avoid the jammer. This motivates the use of random hopping over multiple subchannels as an effective defense mechanism against the denial of service attacks under different levels of traffic uncertainty.

Finally, we consider a case with *multiple channel access points*, each with independent channels from the transmitter and the jammer. This corresponds to the scenario when each node can transmit over multiple channels simultaneously. Packets addressed to each channel access point (or packets to be transmitted on each channel) are stored in a different queue at the transmitter and each packet queue is associated with a particular arrival rate and a Quality of Service requirement, which is related to an average packet delay bound.

The average energy cost of the transmitter increases, i.e., the jamming attack is less successful, as the number of channel access points increases, because the jammer can allocate its energy resources more efficiently over a small number of channel access points with limited targets for jamming. In Nash equilibrium, the jammer sequentially allocates its transmissions depending on the arrival rates and delay requirements of the channels, as long as its average energy constraint allows. Again, we show that the traffic uncertainty decreases the average energy cost of the transmitter and we evaluate this performance gain as a function of the number of channel access points.

These results apply to other MAC models [22] and they are similar to the performance loss of jammers under type/identity uncertainty, i.e., when nodes do not know whether the opponents are selfish or malicious [23]. Therefore, we can make a broader conclusion that different levels of uncertainty in the network can be effectively used to mitigate the denial of service attacks in communication networks.

The rest of the paper is organized as follows. Section II introduces the random access game model with one transmitter and one jammer. The jamming games without queue state information at the jammer is considered in Section III. The extension to the case with full queue state information at the jammer is presented in Sections IV. The possibility of random errors in queue state information is considered in Section V and the additional channel sensing capability is introduced for jammers in Section VI. For different levels of traffic uncertainty, the throughput and energy performance is compared in Section VII under packet delay constraints. This is followed in Section VIII by the analysis of jamming games with multiple transmitters and jammers. The jamming attack scenarios are extended to an arbitrary number of subchannels in Section IX and to multiple channel access points in Section X. Finally, we draw conclusions in Section XI.

II. Random Access Game Model with One Transmitter and One Jammer

We first consider one transmitter node (node 1) and one jammer node (node 2) at a single channel access point as shown in Figure 2. Packets arrive randomly at node 1's queue with rate λ (packets per time slot) and they are transmitted over a single channel. Node 2 does not have its own traffic and jams node 1's transmissions. We assume that each (packet or jamming signal) transmission consumes one unit of energy. We consider a synchronous slotted system, in which each packet transmission (or jamming attempt) takes one time slot. Hence, the jammer cannot wait to detect the start of a transmission before jamming. Later in Section VI, we will consider the effects of channel sensing and allow the jammer to detect any transmission before starting a denial of service attack.

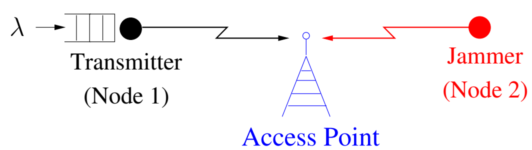

Fig. 2. Single channel access point with one transmitter and one jammer.

We assume that the packet arrivals are independent and identically distributed over time such that it is difficult for the jammer to infer the queue state of the transmitter. We will examine in Section V the effect of random errors in queue state information.

We formulate a *non-cooperative game* in which each node i's action is to choose randomly to transmit or to wait in any time slot. The objectives of node 1 are:

(i) to meet a target minimum rate constraint

$$r(\lambda, D) > \lambda, \tag{1}$$

where the Quality of Service parameter D will be modeled as a packet delay constraint in Section VII, and

(ii) to minimize the average energy cost subject to the rate constraint (i).

The constraint (i) imposes a lower bound on the target rate (number of packets that can be delivered per time slot on the average), which can be also interpreted as the minimum rate that is necessary to keep the average packet delay under a threshold D. We will discuss the relationship between the rate and delay constraints in Section VII.

The objectives of node 2 are:

(i) to maximize the average transmission cost of node 1, and

(ii) to satisfy an upper bound E_2 on its own average energy cost.

Node 1 transmits with probability p_1 only if it has a packet in its queue. This transmission is successful with probability 1, if node 2 does not transmit. The transmitted packet is *captured* with probability q, if node 2 also transmits in the same time slot.

The capture probability q depends on the physical channel properties. It has been computed in [20] as a function of transmission power, channel fading and noise, and its asymptotic value has been derived, as the number of colliding packets tends to infinity. The analysis of capture probability has been extended in [21] to a general model for narrow-band and wide-band systems. We assume that the capture probability is fixed and given. The exact characterization of the capture probability is beyond the scope of this paper.

III. Case (i): No Queue State Information Available at Jammer

We start with the case where jammer node 2 does not know the queue state of transmitter node 1, namely whether node 1 has a packet to transmit or not. In this case, the jammer chooses a fixed transmission probability p_2 for all time. Then, the resulting service rate of node 1's queue is given by

$$\mu(p_1, p_2) = p_1\left((1 - p_2) + p_2 q\right), \tag{2}$$

since node 1's transmission is successfully received only if node 2 does not transmit or node 1's packet transmission is captured with probability q when node 2 also transmits.

The probability that there exists a packet in node 1's queue is given by the utilization factor $\frac{\lambda}{\mu(p_1,p_2)}$ according to Little's result [24]. We assume unit energy cost per transmission for both nodes. Hence, the average energy cost of node 1 is given by $\frac{\lambda}{\mu(p_1,p_2)}\, p_1$. Node 1's objective in this game is to solve the following optimization problem

$$\begin{aligned} \max_{p_1 \in [0,1]} u_1(p_1, p_2) \quad &:= \quad -\frac{\lambda}{\mu(p_1, p_2)} p_1 \\ \text{subject to} \quad &\quad \mu(p_1, p_2) \geq r(\lambda, D). \end{aligned} \tag{3}$$

Node 2 lacks the queue state information of node 1. Therefore, it always chooses between transmitting and waiting with the fixed probability $p_2 \in [0, 1]$ to maximize the average transmission cost of node 1 subject to its average cost constraint given by

$$p_2 \leq E_2, \tag{4}$$

where $0 \leq E_2 \leq 1$.

Node 2 cannot further improve its utility by randomizing p_2 subject to its average energy constraint. If node 2 randomizes its transmission probability with arbitrary distribution, node 1 would receive the average rate that is given by

$$E[\mu(p_1,p_2)] = p_1(1 - E[p_2](1-q)) \quad (5)$$
$$\geq p_1(1 - E_2(1-q)), \quad (6)$$

since $E[p_2] \leq E_2$, where the expectation is taken over random p_2. Therefore, the jammer's best strategy is still to choose a fixed transmission probability, i.e., $E[p_2] = p_2$

Hence, node 2 solves the optimization problem

$$\max_{p_2 \in [0,1]} u_2(p_1,p_2) := \frac{\lambda}{\mu(p_1,p_2)} p_1$$
$$\text{subject to} \quad p_2 \leq E_2. \quad (7)$$

We characterize the outcome of this game by finding the *Nash equilibrium* strategies p_i^*, $i = 1, 2$, which satisfy

$$u_i(p_i^*, p_{-i}^*) \geq u_i(p_i, p_{-i}^*), \ (p_i^*, p_{-i}^*) \in \mathcal{C}, \ i = 1, 2, \quad (8)$$

for any strategy p_i, $i = 1, 2$, where p_{-i} is the strategy of the node other than node i and $\mathcal{C}$ is the constraint set:

$$\mathcal{C} = \{p_i \in [0,1], \ i = 1,2,$$
$$\mu(p_1,p_2) \geq r(\lambda, D), \ p_2 \leq E_2\}. \quad (9)$$

A jammer or transmitter cannot unilaterally deviate from the Nash equilibrium. It can be easily seen that at a Nash equilibrium, the jammer will transmit with maximum probability $p_2 = E_2$.

Given a choice of p_2, it can be seen from (2)-(3) that the average energy of node 1 will not depend on the choice of p_1. Hence, any choice of p_1 that satisfies the target rate constraint

$$\mu(p_1,p_2) \geq r(\lambda, D) \quad (10)$$

will solve (3), provided that such a choice of p_1 exists, which is possible if and only if

$$1 - E_2(1-q) \geq r(\lambda, D). \quad (11)$$

Hence assuming that (11) is satisfied, the set of Nash equilibria of the game are all (p_1^*, p_2^*) satisfying

$$p_1^* \geq \frac{r(\lambda, D)}{1 - p_2^*(1-q)}, \quad (12)$$
$$p_2^* = E_2. \quad (13)$$

If (11) is not satisfied then a Nash equilibrium does not exist. Note that for any of these equilibria, the utilities achieved by the two nodes will sum to zero subject to their individual constraints.

Next, we introduce an average energy constraint E_1 on node 1. The average energy cost of node 1 is given by

$$\frac{\lambda}{\mu(p_1,p_2)} p_1 \leq E_1 \quad (14)$$

and at an equilibrium it can be written as

$$\frac{\lambda}{1 - E_2(1-q)} \leq E_1. \quad (15)$$

Given such constraints (11) and (15), the set of feasible arrival rates for node 1, $\mathcal{S}$, that satisfy (10) is given by

$$\mathcal{S} = \Big\{ \lambda \geq 0 \ : \ r(\lambda, D) \leq 1 - E_2(1-q),$$
$$\lambda \leq E_1 \left(1 - E_2(1-q)\right) \Big\}. \quad (16)$$

If an arrival rate λ is not feasible, node 1 cannot achieve the given target rate $r(\lambda, D)$ and cannot satisfy the delay constraint D. Therefore, the Nash equilibrium does not exist for the jamming game with this arrival rate λ.

IV. Case (*ii*): Full Queue State Information Available at Jammer

Next, we assume that jammer node 2 knows whether transmitter node 1 has a packet to transmit or not. Compared to case (*i*) node 2 can adjust its strategy so as to conserve energy (by not transmitting) when node 1 does not have a packet. With queue state information node 2 will only transmit with probability p_2, if the queue of node 1 is not empty. Thus, node 2's average transmission cost becomes $\frac{\lambda}{\mu(p_1,p_2)} p_2$, which is smaller than the cost in case (*i*) with no queue state information at the jammer (namely, p_2). Hence, the optimization problem facing node 2 is now

$$\max_{p_2 \in [0,1]} u_2(p_1,p_2) := \frac{\lambda}{\mu(p_1,p_2)} p_1$$
$$\text{subject to} \quad \frac{\lambda}{\mu(p_1,p_2)} p_2 \leq E_2. \quad (17)$$

Node 2 chooses p_2 as large as possible in Nash equilibrium. The problem facing node 1 is the same as in case (*i*) with no queue state information and so any choice of p_1 which satisfies target rate constraint (10) will be a Nash equilibrium provided that one exists. In case (*i*) we noted from Eq. (12) that there exist multiple Nash equilibria all leading to the same energy cost for node 1. In case (*i*) there may be multiple Nash equilibria; however, a key difference here is that now node 1's pay-off is not the same in each of these equilibria because a change in node 1's action influences the energy constraint for node 2. As node 1 decreases its transmission probability, node 2 must also, which improves the equilibrium pay-off of node 1. The resulting "best" Nash equilibrium strategies (namely, the Nash equilibrium strategies leading to the minimum energy cost for node 1) are given by

$$p_1^* = \frac{r(\lambda, D)}{1 - p_2^*(1-q)}, \quad (18)$$
$$p_2^* = \left(E_2 \frac{r(\lambda, D)}{\lambda} \right)_{\leq 1}, \quad (19)$$

where we define $(x)_{\leq 1} := \min(x, 1)$. The equilibrium strategies (18) and (19) are possible only if

$$r(\lambda, D) \leq 1 - p_2^*(1-q). \quad (20)$$

Otherwise, a Nash equilibrium does not exist. If we impose the average energy constraint E_1 on node 1, the set of feasible arrival rates for node 1, $\mathcal{S}$, is given by

$$\mathcal{S} = \Big\{\lambda \geq 0 : r(\lambda, D) \leq 1 - \Big(E_2 \frac{r(\lambda, D)}{\lambda}\Big)_{\leq 1}(1-q), \quad \lambda \leq E_1\Big(1 - \Big(E_2\frac{r(\lambda, D)}{\lambda}\Big)_{\leq 1}(1-q)\Big)\Big\}. \quad (21)$$

The maximum feasible rate in (21) is smaller than the maximum feasible rate in (16), which implies that a jamming attack is more effective in case (*ii*). Also note that the maximum rates in (16) and (21) approach each other, as λ increases to $r(\lambda, D)$ such that the transmitter queue becomes saturated and the queue state information loses its value.

V. Case (*iii*): Random Errors in Queue State Information Available at Jammer

Now, we consider a mixed case in which the jammer observes the channel outcomes and infers the queue state of the transmitter. Because of the stochastic nature of packet arrivals, the jammer possibly makes an error with probability Δ in identifying whether node 1's queue is empty or not. This models the uncertainty level for the jammer's detection of node 1's queue state. Note that the false alarm and missed opportunity for the jamming attack can be observed by both nodes through the channel outcomes. This allows both transmitter and jammer nodes to compute Δ. Therefore, in steady state we can assume that both nodes already know the exact value of Δ. Node 2 transmits with probability p_2 only, if it believes that node 1 has a packet to transmit (which would be true with probability $1-\Delta$). Then, the service rate of node 1 is changed to

$$\mu(p_1, p_2) = p_1(1 - (1-\Delta)p_2(1-q)), \quad (22)$$

whereas the average energy constraint of node 2 is given by

$$\Big(\frac{\lambda}{\mu(p_1,p_2)}(1-\Delta) + \Big(1 - \frac{\lambda}{\mu(p_1,p_2)}\Big)\Delta\Big)\, p_2 \leq E_2. \quad (23)$$

Node 2 chooses p_2 as large as possible, while node 1 chooses any p_1 as long as it satisfies the target rate constraint. There exist multiple Nash equilibria as in the previous cases (*i*) and (*ii*). The Nash equilibrium solution that results in the minimum energy cost for node 1 satisfies the target rate constraint given by (10) with equality. The resulting Nash equilibrium strategies are given as function of Δ as

$$p_1^* = \frac{r(\lambda, D)}{1 - (1-\Delta)p_2^*(1-q)}, \quad (24)$$

$$p_2^* = \left(\frac{E_2}{\frac{\lambda}{r(\lambda,D)}(1-2\Delta) + \Delta}\right)_{\leq 1} \quad (25)$$

provided that $p_1^* \leq 1$, which is possible if and only if

$$r(\lambda, D) \leq 1 - (1+\Delta)p_2^*(1-q), \quad (26)$$

Note that $\frac{\lambda}{r(\lambda,D)}(1-2\Delta) + \Delta \geq 0$, since $\frac{\lambda}{r(\lambda,D)} \leq 1$. Hence, we have $p_2^* \geq 0$ in Eq. (25).

If we impose an average energy constraint E_1 for node 1, the set of feasible arrival rates for node 1, $\mathcal{S}$, is limited to

$$\mathcal{S} = \Big\{\lambda \geq 0 : \; r(\lambda, D) \leq 1 - (1-\Delta)\, p_2^*\,(1-q), \quad \lambda \leq E_1\Big(1 - (1-\Delta)\, p_2^*\,(1-q)\Big)\Big\}, \quad (27)$$

where p_2^* is given by Eq. (25).

Note that the service rate achievable by the transmitter in case (*iii*) is always smaller than the rate in case (*ii*) with full queue state information at the jammer. On the other hand, queue state information with random errors in case (*iii*) reduces the service rate (and increases the energy cost) of the transmitter compared to case (*i*) without any queue state information at the jammer, only if $\Delta < \frac{1}{2}$. Otherwise, the possible errors in queue state information mislead the jammer to make transmission decisions worse than in case (*i*).

VI. Jamming with Channel Sensing Capability

Next, we consider a Carrier Sense Multiple Access (CSMA) system, in which the jammer senses the channel and knows not only the queue state of the transmitter but also when it transmits at any given time slot. For that purpose, we assume that node 2 listens to the channel continuously (except when it is transmitting) to see when node 1 begins transmitting and then starts to jam node 1's transmission with probability p_2, if the average energy constraint

$$\frac{\lambda}{\mu(p_1,p_2)}p_1 p_2 \leq E_2 \quad (28)$$

allows. The service rate of node 1 is still given by (2). Node 1 chooses p_1 to satisfy the target rate constraint and node 2 chooses p_2 as large as possible to satisfy (28). The resulting Nash equilibrium strategies are computed as

$$p_1^* \geq \frac{r(\lambda, D)}{1 - p_2^*(1-q)}, \quad (29)$$

$$p_2^* = \left(\frac{E_2}{\lambda + E_2(1-q)}\right)_{\leq 1}. \quad (30)$$

Note that p_2^* in (30) is independent of $r(\lambda, D)$ and leads to a larger energy cost for node 1 compared to case (*ii*) (unless $p_2^* = 1$ in both (19) and (30) with the same energy cost for both cases). For the average energy constraint E_1 on node 1, the set of feasible arrival rates, $\mathcal{S}$, is reduced to

$$\mathcal{S} = \Big\{\lambda \geq 0 : \; r(\lambda, D) \leq 1 - \left(\frac{E_2}{\lambda + E_2(1-q)}\right)_{\leq 1}(1-q), \quad \lambda \leq E_1\Big(1 - \Big(\frac{E_2}{\lambda + E_2(1-q)}\Big)_{\leq 1}(1-q)\Big)\Big\}. \quad (31)$$

VII. Feasible Throughput Performance of Jamming Games under a Delay Constraint

We relate the target rate constraint $r(\lambda, D)$ to an average delay constraint D. Node 1 retransmits each packet until it is successfully received. Hence the service time of a packet is a *geometric* random variable with success rate $\mu(p_1, p_2)$. Assuming Poisson arrivals, we can view the packets as being placed in a $M/Geo/1$ queue. The average total packet delay $T(\lambda, p_1, p_2)$ is given by the Pollaczek-Khinchin formula [24]:

$$T(\lambda, p_1, p_2) = \frac{2-\lambda}{2(\mu(p_1,p_2) - \lambda)}. \quad (32)$$

The delay constraint $T(\lambda, p_1, p_2) \leq D$ is equivalent to the service rate constraint $\mu(p_1, p_2) \geq r(\lambda, D)$, where

$$r(\lambda, D) = \frac{(2D-1)\lambda + 2}{2D}. \qquad (33)$$

First, we evaluate the maximum feasible throughput rates given by (16) and (21) for both cases with and without queue state information at the jammer. Figure 3 shows the maximum feasible throughput rate as function of delay constraint D for different energy bounds E_1 and E_2, where $q = 0$. Figure 4 shows the maximum feasible throughput rate as function of delay constraint D for different capture probabilities q, where $E_1 = 0.75$ and $E_2 = 0.25$.

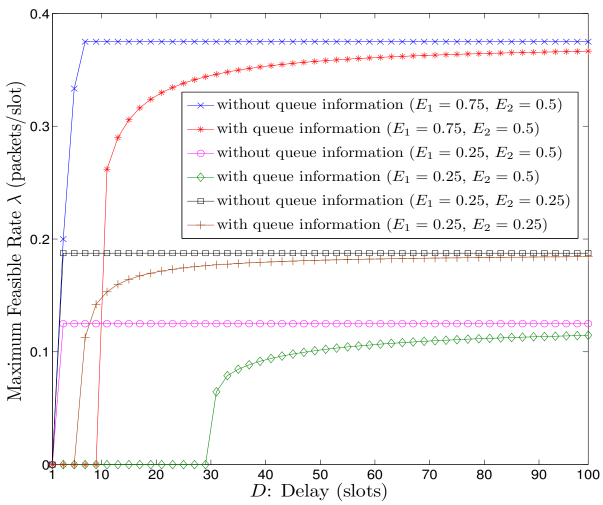

Fig. 3. The maximum feasible rate for a single transmitter-jammer pair with different energy bounds, where $q = 0$.

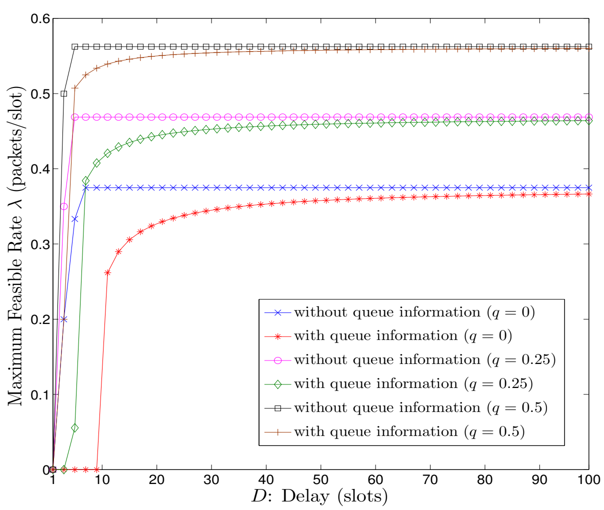

Fig. 4. The maximum feasible rate for a single transmitter-jammer pair with different capture probabilities, where $E_1 = 0.75$ and $E_2 = 0.25$.

Our findings show that the transmitter increases its feasible throughput, when the queue state information is not available at the jammer. This throughput gain is especially large when the delay constraint D, capture probability q or jammer energy bound E_2 is small. The maximum feasible throughput of the transmitter increases with D, q, and transmitter energy bound E_1, and it decreases with E_2. On the other hand, as D increases, the transmitter queue becomes backlogged and the queue state information at the jammer loses its effect on the jamming game.

Next, we compare the jamming attacks for the cases with possible errors in queue state information and with channel sensing. The maximum feasible throughput rates given by (16), (21), (27) and (31) are illustrated in Figure 5 as function of D for $E_1 = 0.75$, $E_2 = 0.5$, and $q = 0$. The feasible rates expand with the increasing error in queue state information. On the other hand, jamming with channel sensing provides a lower bound on the feasible rates achievable by the transmitter.

We also compare in Figure 6 the equilibrium utility (average energy cost) of node 1 for $E_1 = 1$, $\lambda = 0.25$, $D = 20$, and $q = 0$. The results verify that the transmitter energy cost increases with the increasing level of information available at the jammer provided that the equilibrium solutions exist.

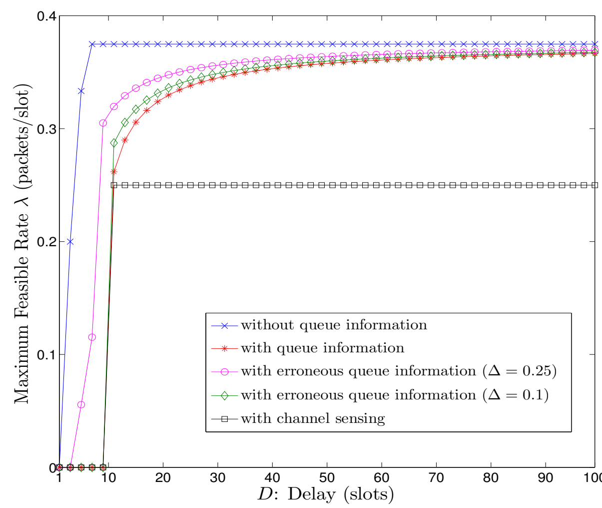

Fig. 5. The maximum feasible rate for a single transmitter-jammer pair with different models of traffic uncertainty, where $E_1 = 0.75$, $E_2 = 0.5$, and $q = 0$.

VIII. Jamming Games for an Arbitrary Number Transmitters and Jammers

We extend the model to n_T selfish nodes transmitting at a single channel access point with n_J jammers. We assume a *symmetric* system, in which transmitters and jammers have the common constraints of average energy costs E_T and E_J, respectively. The total arrival rate is λ and the arrival rate for each of n_T transmitters is $\frac{\lambda}{n_T}$. Each transmitter has the same target rate constraint $r(\frac{\lambda}{n_T}, D)$, which can be related to a delay parameter D. All transmitters and jammers have the common transmission probabilities p_T and p_J, respectively. Any packet transmission is successfully received with capture probability q_n, if n other nodes (transmitter or jammer) transmit at the same time. In this symmetric case, the maximum common stable throughput equals the common throughput of the backlogged system. Then, the common service rate for each transmitter queue is given by

$$\mu(p_T, p_J) = p_T \, \tilde{p}(p_T, p_J), \qquad (34)$$

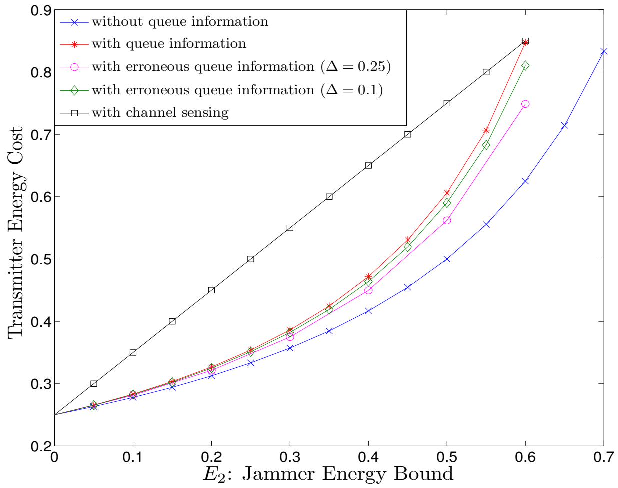

Fig. 6. The transmitter average energy cost for a single transmitter-jammer pair, where $E_1 = 1$, $\lambda = 0.25$, $D = 20$, and $q = 0$.

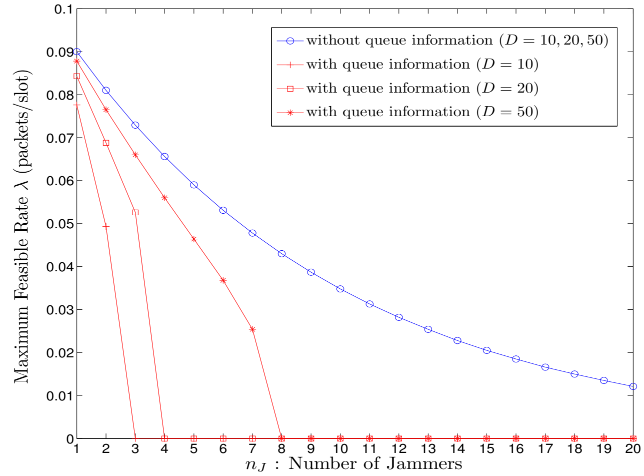

Fig. 7. The maximum feasible rate for one transmitter and multiple jammers, where $E_T = 0.1$, $E_J = 0.1$, $q_0 = 1$, and $q_n = 0$, $n > 0$.

where

$$\tilde{p}(p_T, p_J) = \sum_{i=0}^{n_T-1} \sum_{j=0}^{n_J} \binom{n_T - 1}{i} \binom{n_J}{j} \times q_{i+j} (p_T)^i (1 - p_T)^{n_T-1-i} (p_J)^j (1 - p_J)^{n_J-j}. \quad (35)$$

Each transmitter minimizes its own average energy cost $\frac{\lambda}{\mu(p_T,p_J)} p_T$ while satisfying the target rate constraint

$$\mu(p_T, p_J) \geq r\Big(\frac{\lambda}{n_T}, D\Big). \quad (36)$$

If jammers do not have queue state information of transmitters, the symmetric equilibrium strategies are given by

$$p_T^* \geq \frac{r\big(\frac{\lambda}{n_T}, D\big)}{\tilde{p}(p_T^*, p_J^*)}, \quad (37)$$

$$p_J^* = E_J, \quad (38)$$

provided that $r\big(\frac{\lambda}{n_T}, D\big) \leq p_T^* \tilde{p}(p_T^*, p_J^*)$ and $E_J \leq 1$ such that $p_T^* \leq 1$ and $p_J^* \leq 1$, respectively.

Otherwise, if jammers know whether the transmitter queues are all empty, or there is at least one packet to transmit, there exist again multiple symmetric Nash equilibria for transmitters. The best equilibrium strategies leading to the minimum energy cost for transmitters satisfy the target rate constraint (36) with equality. These symmetric equilibrium strategies are given by

$$p_T^* = \frac{r\big(\frac{\lambda}{n_T}, D\big)}{\tilde{p}(p_T^*, p_J^*)}, \quad (39)$$

$$p_J^* = \left(\frac{E_J \, n_T \, r\big(\frac{\lambda}{n_T}, D\big)}{\lambda} \right)_{\leq 1}. \quad (40)$$

From (37)-(40), the transmission probability of jammers increases compared to the case without queue state information. This reduces the maximum feasible throughput rates of transmitters (under the average energy constraint E_T), as shown in Figure 7 for $n_T = 1$. Without queue state information, the feasible rates quickly converge to a constant, as D increases, as shown in Figures 3 and 4 for $n_T = n_J = 1$.

IX. Extension to Multiple Subchannels

We continue with one transmitter-jammer pair and extend the model to n independent subchannels from transmitter node 1 and jammer node 2 to a single channel access point. Node $j = 1, 2$ transmits on subchannel $i = 1, ..., n$ independently with probability $p_{j,i}$. We assume that each node (transmitter or jammer) can transmit over at most one subchannel in one time slot. Therefore, $\sum_{i=1}^{n} p_{j,i} \leq 1$. The total arrival rate at node 1 is λ and the delay constraint is D. Node 1 buffers all packets in a single queue and the service rate is given by

$$\mu\left(\{p_{1,i}, p_{2,i}\}_{i=1}^{n}\right) = \sum_{i=1}^{n} p_{1,i}(1 - p_{2,i}(1 - q_i)), \quad (41)$$

where q_i is the capture probability on subchannel i. Node 1 chooses $p_{1,i} \in [0, 1]$ to minimize the total energy cost subject to the target rate constraint $r(\lambda, D)$, namely solves

$$\max_{\{p_{1,i}\}_{i=1}^{n}} \quad u_1\left(\{p_{1,i}, p_{2,i}\}_{i=1}^{n}\right) := -\frac{\lambda}{\mu\left(\{p_{1,i}, p_{2,i}\}_{i=1}^{n}\right)} \sum_{i=1}^{n} p_{1,i}$$
$$\text{subject to} \quad \mu\left(\{p_{1,i}, p_{2,i}\}_{i=1}^{n}\right) \geq r(\lambda, D). \quad (42)$$

Without queue state information of node 1, node 2 maximizes the total energy cost of node 1 and solves the optimization problem

$$\max_{\{p_{2,i}\}_{i=1}^{n}} \quad u_2\left(\{p_{1,i}, p_{2,i}\}_{i=1}^{n}\right) := \frac{\lambda}{\mu\left(\{p_{1,i}, p_{2,i}\}_{i=1}^{n}\right)} \sum_{i=1}^{n} p_{1,i}$$
$$\text{subject to} \quad \sum_{i=1}^{n} p_{2,i} \leq E_2. \quad (43)$$

In Nash equilibrium, both nodes 1 and 2 make each other indifferent to their actions. The transmission strategies $p_{1,i}$ and $p_{2,i}$ affect each other through the service rate formulation (41). In particular, if transmitter node 1 chooses $\{p_{1,i}\}_{i=1}^n$ to satisfy $p_{1,i}(1-q_i) = c_1$ for all $i = 1, ..., n$, where c_1 is a constant, then jammer node 2 cannot change (and further improve) its utility $u_2\left(\{p_{1,i}, p_{2,i}\}_{i=1}^n\right)$ by changing its strategies $\{p_{2,i}\}_{i=1}^n$ as long as these strategies satisfy the energy constraint with equality, i.e., $\sum_{i=1}^n p_{2,i} = E_2$.

Similarly, if jammer node 2 chooses $\{p_{2,i}\}_{i=1}^n$ to satisfy $p_{2,i}(1-q_i) = c_2$ for all $i = 1, ..., n$, where c_2 is a constant, then also transmitter node 1 cannot improve its utility $u_1\left(\{p_{1,i}, p_{2,i}\}_{i=1}^n\right)$ by changing its strategies $\{p_{1,i}\}_{i=1}^n$ as long as these strategies satisfy the target rate constraint, i.e., $\mu\left(\{p_{1,i}, p_{2,i}\}_{i=1}^n\right) \geq r(\lambda, D)$.

As a result, the conditions for the existence of the Nash equilibrium strategies $p_{j,i}^*$ for node j on subchannel i are

$$p_{j,i}^*(1-q_i) = c_j, \quad j = 1, 2, \ \ i = 1, ..., n. \tag{44}$$

Then, the Nash equilibrium solutions for $i = 1, ..., n$ follow from (44) as

$$p_{1,i}^* \geq \frac{r(\lambda, D)}{(1-q_i)\left(\left(\sum_{i=1}^n \frac{1}{1-q_i}\right) - E_2\right)}, \tag{45}$$

$$p_{2,i}^* = \frac{E_2}{(1-q_i)\sum_{i=1}^n \frac{1}{1-q_i}}. \tag{46}$$

Note that these equilibrium solutions are possible only if $\sum_{i=1}^n p_{1,i} \leq 1$, i.e., only if

$$r(\lambda, D) \leq \frac{\left(\sum_{i=1}^n \frac{1}{1-q_i}\right) - E_2}{\sum_{i=1}^n \frac{1}{(1-q_i)}}. \tag{47}$$

Next, we impose an energy constraint E_1 on node 1:

$$\frac{\lambda}{1 - \frac{E_2}{\sum_{i=1}^n \frac{1}{1-q_i}}} \leq E_1. \tag{48}$$

Given constraints (47) and (48), the set of feasible arrival rates for node 1, $\mathcal{S}$, is given by

$$\mathcal{S} = \Bigg\{\lambda \geq 0 \ : \ r(\lambda, D) \leq \frac{\left(\sum_{i=1}^n \frac{1}{1-q_i}\right) - E_2}{\sum_{i=1}^n \frac{1}{(1-q_i)}}, \quad \lambda \leq E_1\left(1 - \frac{E_2}{\sum_{i=1}^n \frac{1}{1-q_i}}\right)\Bigg\}. \tag{49}$$

If we assume that the jammer knows whether the transmitter has a packet to transmit or not, the energy constraint for the optimization problem solved by the jammer is changed to

$$\frac{\lambda}{\mu\left(\{p_{1,i}, p_{2,i}\}_{i=1}^n\right)} \sum_{i=1}^n p_{2,i} \leq E_2, \tag{50}$$

since the transmitter has a packet to transmit with probability $\frac{\lambda}{r(\lambda,D)}$. The structure of the equilibrium solutions remains the same as in (45) and (46) with E_2 replaced with $\min\left(E_2 \frac{r(\lambda,D)}{\lambda}, 1\right)$, and again there exist multiple Nash equilibria. The equilibrium strategies of node 1 that minimize the energy cost of the transmitter satisfy the target rate constraint with equality, i.e., $\mu\left(\{p_{1,i}, p_{2,i}\}_{i=1}^n\right) = r(\lambda, D)$. These Nash equilibrium solutions are given by

$$p_{1,i} = \frac{r(\lambda, D)}{(1-q_i)\left(\left(\sum_{i=1}^n \frac{1}{1-q_i}\right) - \min\left(E_2 \frac{r(\lambda,D)}{\lambda}, 1\right)\right)}, \tag{51}$$

$$p_{2,i} = \frac{\min\left(E_2 \frac{r(\lambda,D)}{\lambda}, 1\right)}{(1-q_i)\sum_{i=1}^n \frac{1}{1-q_i}}. \tag{52}$$

For the two cases with and without queue state information at the jammer, the maximum feasible throughput rates are evaluated in Figure 8 as function of the number of subchannels for different capture probabilities and for different energy costs of the transmitter and the jammer, where $D = 10$.

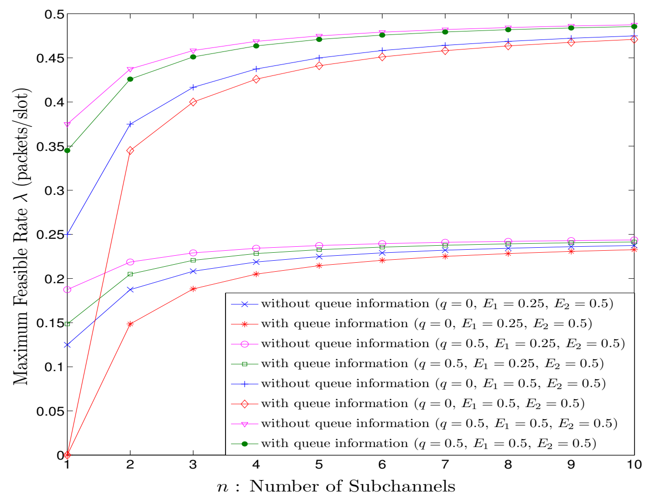

Fig. 8. The maximum feasible rate as function of the number of subchannels, where $D = 10$.

As the number of subchannels, n, increases, the performance gap between the two cases with and without queue state information at the jammer decreases. The reason is that with increasing n there are more possibilities for the transmitter to avoid jamming. Therefore, random hopping among an increasing number of channels provides an additional defense mechanism against the denial of service attacks and this reduces the effect of queue state information at the jammer on the throughput performance of the transmitter.

X. Jamming at Multiple Channel Access Points

Next, we extend the model to n channel access points, each with an independent channel from transmitter node 1 and jammer node 2, as shown in Figure 9. Node 1 randomly transmits over each of n channels simultaneously and node 2 attempts to jam the transmissions on each channel subject to its average cost constraint over all channels.

The packet traffic of node 1 is split to the individual channels and the packets to be transmitted on each channel $i \in \{1, ..., n\}$ are buffered in a separate queue with average packet delay constraint D_i, service rate μ_i, and arrival rate λ_i such that

$$\sum_{i=1}^n \lambda_i = \lambda. \tag{53}$$

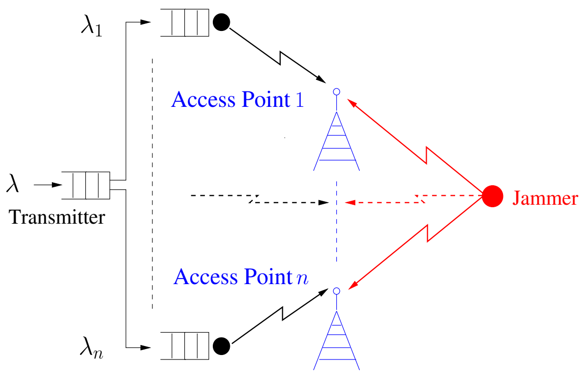

Fig. 9. Multiple channel access points with one transmitter and one jammer.

We assume fixed traffic rates $\{\lambda_i\}_{i=1}^n$ and delay requirements $\{D_i\}_{i=1}^n$ such that the target service rate on channel i is $r_i(\lambda_i, D_i)$. Different delay and target rate conditions reflect the general heterogeneous case in which each packet stream addressed to a different channel access point is subject to a different Quality of Service requirement.

Node $j = 1, 2$ transmits on channel $i = 1, ..., n$ independently with probability $p_{j,i}$ and the service rate is

$$\mu_i(p_{1,i}, p_{2,i}) = p_{1,i}(1 - (1 - q_i)p_{2,i}), \quad (54)$$

where q_i is the capture probability of channel i. Node 1 chooses $p_{1,i} \in [0, 1]$ to minimize the total energy cost subject to the target rate constraint on each channel, namely solves the optimization problem

$$\begin{aligned} \max_{\{p_{1,i}\}_{i=1}^n \in [0,1]^n} \quad & u_1\left(\{p_{1,i}, p_{2,i}\}_{i=1}^n\right) \\ & := -\sum_{i=1}^n \frac{\lambda_i}{\mu_i(p_{1,i}, p_{2,i})} p_{1,i} \\ \text{subject to} \quad & \mu(p_{1,i}, p_{2,i}) \geq r_i(\lambda_i, D_i), i = 1, ..., n. \quad (55) \end{aligned}$$

Without queue state information for node 1, node 2 solves the optimization problem

$$\begin{aligned} \max_{\{p_{2,i}\}_{i=1}^n \in [0,1]^n} \quad & u_2\left(\{p_{1,i}, p_{2,i}\}_{i=1}^n\right) \\ & := \sum_{i=1}^n \frac{\lambda_i}{\mu_i(p_{1,i}, p_{2,i})} p_{1,i} \\ \text{subject to} \quad & \sum_{i=1}^n p_{2,i} \leq E_2. \quad (56) \end{aligned}$$

For $E_2 \leq 1$, the jammer transmits only on one channel and the equilibrium strategies are given by

$$\begin{aligned} p^*_{2,i^*} &= E_2 \\ \text{for } i^* &= \arg\max_{i=1,...,n} \left(\frac{1}{1 - E_2(1 - q_i)} - 1\right) \lambda_i. \quad (57) \end{aligned}$$

If i^* is not unique, the jammer arbitrarily chooses one channel from i^* and transmits with probability E_2 on that channel.

For $E_2 > 1$, node 2 transmits on multiple channels i^*_k, $k = 1, ..., \lceil E_2 \rceil$, with non-zero transmission probabilities p_{2,i^*_k}. We iteratively specify the equilibrium strategies p^*_{2,i^*_k} as follows:

$$\begin{aligned} p^*_{2,i^*_k} &= (E_{2,k})_{\leq 1} \\ \text{for } i^*_k &= \arg\max_{i \in S_k} \left(\frac{1}{1 - (E_{2,k})_{\leq 1}(1 - q_i)} - 1\right) \lambda_i, \\ k &= 1, ..., \lceil E_2 \rceil, \quad (58) \end{aligned}$$

where

$$S_{k+1} = S_k - \{i^*_k\} \quad (59)$$

is the set of the remaining channels after selecting the first k channels to jam, and

$$E_{2,k+1} = E_{2,k} - p^*_{2,i^*_k} \quad (60)$$

is the energy budget left after jamming k channels. The initial set is $S_1 = \{1, ..., n\})$ with $E_{2,1} = E_2$.

If i^*_k is not unique, node 2 jams only one channel from i^*_k, which is subsequently removed from S_k to form S_{k+1}. For the equilibrium strategies $p^*_{2,i}$ of the jammer, node 1 chooses its transmission probability $p_{1,i}$ to satisfy the rate constraint

$$\mu_i(p_{1,i}, p^*_{2,i}) \geq r_i(\lambda_i, D_i). \quad (61)$$

If the jammer knows the queue state for packets to be transmitted on each channel, the optimization problem solved by node 2 is changed to

$$\begin{aligned} \max_{\{p_{2,i}\}_{i=1}^n} \quad & \sum_{i=1}^n \frac{\lambda_i}{\mu_i(p_{1,i}, p_{2,i})} p_{1,i} \\ \text{subject to} \quad & \sum_{i=1}^n \frac{\lambda_i}{r_i(\lambda_i, D_i)} p_{2,i} \leq E_2. \quad (62) \end{aligned}$$

Node 2 transmits on possibly multiple channels i^*_k, $k = 1, ..., \lceil E_2 \rceil$, with non-zero transmission probabilities p_{2,i^*_k}. The equilibrium strategies p^*_{2,i^*_k} are iteratively specified as follows:

$$\begin{aligned} p^*_{2,i^*_k} &= \left(\frac{E_{2,k} r_k(\lambda_k, D_k)}{\lambda_k}\right)_{\leq 1} \\ i^*_k &= \arg\max_{i \in S_k} \left(\frac{1}{1 - \left(\frac{E_{2,k} r_k(\lambda_k, D_k)}{\lambda_k}\right)_{\leq 1}(1 - q_i)} - 1\right) \lambda_i, \quad (63) \end{aligned}$$

where S_k is defined as before in (59) and $E_{2,k}$ is given by

$$E_{2,k+1} = E_{2,k} - \frac{\lambda_k}{r_k(\lambda_k, D_k)} p^*_{2,i^*_k}. \quad (64)$$

Any set of transmission probabilities $\{p_{1,i}\}_{i=1}^n$ satisfying the target rate constraint (61) for each channel constitutes a Nash equilibrium. To achieve the smallest energy cost, node 1 chooses the transmission probability $p_{1,i}$ to satisfy the rate constraint with equality, namely

$$\mu_i(p_{1,i}, p^*_{2,i}) = r_i(\lambda_i, D_i) \quad (65)$$

If the jammer does not know $\{\lambda_i\}_{i=1}^n$ and $\{q_i\}_{i=1}^n$, it could only spread its transmission probabilities $\{p_{2,i}\}_{i=1}^n$ uniformly over all channels. However, this random strategy cannot maximize the jammer's utility because of the uncertainty on the heterogeneous traffic and channel conditions.

The average energy cost of the transmitter is evaluated in Figure 10 (for symmetric channels with $\lambda = 0.1$, $q_i = 0.25$, $\lambda_i = \frac{\lambda}{n}$, and $D_i = 20$, $i = 1, ..., n$) as function of the energy bound for the jammer, E_2, and the number of channels, n. The jamming attack starts failing (in terms of maximizing the average energy cost of the transmitter), as the number of channels increases. Although the jammer can simultaneously jam multiple channels, it is subject to a total energy constraint and the transmitter can effectively allocate its energy among transmissions over multiple channels to avoid jamming.

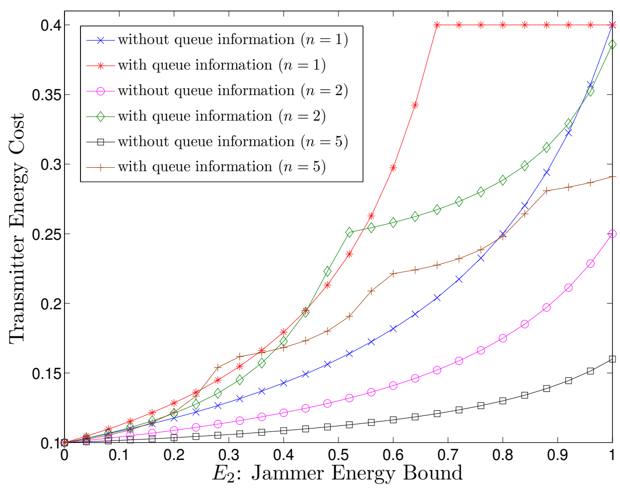

Fig. 10. The average energy cost of the transmitter as function of the number of channels, where $\lambda = 0.1$, $q_i = 0.25$, $\lambda_i = \frac{\lambda}{n}$, and $D_i = 20$, $i = 1, ..., n$.

XI. Conclusions

We examined jamming games in random access-based MAC models and evaluated the effects of stochastically varying packet traffic on jamming attacks. We formulated a non-cooperative game where the transmitters and jammers choose their transmission probabilities to access collision channels with random packet capture effects. First, we compared two jamming attack scenarios with and without queue state information at the jammer. Then, we considered random errors in queue state information and introduced channel sensing capability for the jammer. For different levels of traffic uncertainty, the maximum feasible throughput was evaluated at the Nash equilibrium subject to the packet delay and energy constraints. The jamming game model was also extended to multiple transmitters, jammers, subchannels, and channel access points.

Our findings verified the significant performance loss of jammers (i.e., transmitters can effectively improve their feasible throughput), if the packet traffic is stochastically varying and the queue state information is not available at jammers. We showed how the stable throughput rates sustained by transmitters improve with the increasing traffic uncertainty due to the stochastic nature of packet arrivals.

Future work should extend these results to jamming attacks at the network layer, where packet flows are dynamically varying among different routes and the success of jamming attacks depends on whether the packet traffic is instantaneously available on the individual links to be jammed.

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