

Performance Limits of Greedy Maximal Matching in Multi-hop Wireless Networks

Changhee Joo, Xiaojun Lin, and Ness B. Shroff

Abstract—In this paper, we characterize the performance limits of an important class of scheduling schemes, called *Greedy Maximal Matching (GMM)*, for multi-hop wireless networks. For simplicity, we focus on the well-established *node-exclusive* interference model, although many of the stated results can be readily extended to more general interference models. The study of the performance of *GMM* is intriguing because although a lower bound on its performance is well known, empirical observations suggest that this bound is quite loose, and that the performance of *GMM* is often close to optimal. In fact, recent results have shown that *GMM* achieves optimal performance under certain conditions. In this paper, we provide new analytic results that characterize the performance of *GMM* through the topological properties of the underlying graphs. To that end, we generalize a recently developed topological notion called the *local pooling* condition to a far weaker condition called the σ -*local pooling*. We then define the *local-pooling factor* on a graph, as the supremum of all σ such that the graph satisfies σ -local pooling. We show that for a given graph, the efficiency ratio of *GMM* (i.e., the worst-case ratio of the throughput of *GMM* to that of the optimal) is equal to its local-pooling factor. Further, we provide results on how to estimate the local-pooling factor for arbitrary graphs and show that the efficiency ratio of *GMM* is no smaller than $d^*/(2d^* - 1)$ in a network topology of maximum node-degree d^* . We also identify a specific network topology for which the efficiency ratio of *GMM* is strictly less than 1.

I. INTRODUCTION

Over the last few years there has been significant interest in studying the *scheduling* problem for multi-hop wireless networks [1]–[9]. In general, this problem involves determining which links should transmit (i.e., which node-pairs should communicate) and at what times, what modulation and coding schemes should be used, and at what power levels should communication take place. While the optimal solution of this scheduling problem has now been known for a long time [2], the resultant solution is extremely complex and virtually impossible to implement.

Recently, several researchers have developed simpler scheduling solutions for an important class of interference models called the *node-exclusive* (or *primary*) interference model. Under this interference model, a node cannot simultaneously transmit or receive, and cannot simultaneously communicate with two or more nodes in the network. The node-exclusive model is a good representation for practical wireless systems using Bluetooth or FH-CDMA networks [1], [10], [11]. Under this model, the scheduling problem can be

mapped to a *matching* problem, i.e., any active set of links must form a *matching* of the nodes in the network. In this setting, there exists a polynomial-time optimal solution called the *Maximum Weighted Matching (MWM)* policy. However, the complexity of *MWM* is roughly $O(N^3)$ [12], where N is the total number of nodes in the network. Hence, it is still too complex to implement in most practical scenarios.

To address this issue, a well-known suboptimal solution called the *Greedy Maximal Matching (GMM)* has been developed that significantly reduces the scheduling complexity [1], [13], [14]. We can characterize the performance of *GMM* through its efficiency ratio γ^* , which is the largest number γ such that for any offered load $\vec{\lambda}$ that the optimal *MWM* policy can support, *GMM* can support $\gamma\vec{\lambda}$. It is relatively straightforward to show that the efficiency ratio of *GMM* is at least $1/2$, i.e., *GMM* can sustain at least half of the throughput of the optimal *MWM* policy. In fact, simulation results suggest that the performance of *GMM* is often much better than this lower bound in most network settings. Further, it has been shown recently that if the network topology satisfies the so-called *local pooling* condition [15], [16], then *GMM* can in fact achieve the full capacity region. Unfortunately, realistic network topologies may not satisfy the local pooling condition, and hence their true efficiency ratio remains unknown.

In this paper, our main contribution is to provide new analytical results on the achievable efficiency ratio of *GMM* for a large class of network topologies. Such an evaluation is important for the following reasons:

- It has been empirically observed in [3] that the throughput achieved by *GMM* is virtually the same as the maximum achievable throughput for a variety of networking scenarios.
- *GMM* can be implemented in a distributed manner [17], which is critical from the point of view of many multi-hop networking systems. Further, even simpler constant-time-complexity random algorithms can be developed to approximate the performance of *GMM* [3].
- Although many distributed scheduling schemes have been recently developed [6], [8], [9], the study of *GMM* continues to remain attractive because, empirically, *GMM* performs better than these schemes [7], either in terms of the achievable throughput, or in terms of the resultant queueing delay.

In this paper, we provide two main results along this direction. First, we generalize the notion of local pooling in [15], and derive an equivalent characterization of the efficiency ratio of *GMM* through a topological property, i.e., the *local-*

C. Joo and N. B. Shroff are currently with The Ohio State University, USA. Email: {cjoo, shroff}@ece.osu.edu

X. Lin is with Electrical and Computer Engineering, Purdue University, USA. Email: linx@ecn.purdue.edu

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pooling factor, of the underlying network graph. In particular, we show that the efficiency ratio of *GMM* under a given network topology is equal to its local-pooling factor. Second, we provide preliminary results for estimating the local-pooling factor of arbitrary network graphs. Using these results, we are able to identify network topologies where the efficiency ratio of *GMM* could be low.

The rest of the paper is organized as follows. We first describe our model in Section II. We then introduce the notion of local-pooling factor and show in Section III that the efficiency ratio of *GMM* under an arbitrary network topology is equal to its local-pooling factor. In Section IV, by characterizing the set of unstable links under *GMM*, we provide preliminary results for estimating the local-pooling factors under arbitrary network graphs. These results lead to the discovery of network graphs where the efficiency ratio of *GMM* is low. We conclude in Section V.

II. NETWORK MODEL

We model a wireless network by a graph $G(V, E)$, where V is the set of nodes, and E is the set of undirected links. We assume a time-slotted system, where the length of each time-slot is of unit length. We assume that in each time-slot, a link can transmit one packet provided that the following *node-exclusive interference* constraint is satisfied: if a link l is transmitting data, then no other links that share a common transmitter node or receiver node with link l can transmit at the same time. Hence, any active set of links must form a *matching* of the nodes in V .

Let M_E be a *maximal matching* on E , i.e., no more links can be added to M_E without violating the node-exclusive interference constraint. We use a vector in $\{0, 1\}^{|E|}$ to denote a maximal matching M_E such that the k -th element is set to 1 if link $k \in E$ is included in the maximal matching M_E , and to 0 otherwise. Let \mathcal{M}_E be the set of all possible maximal matchings and let $Co(\mathcal{M}_E)$ denote its convex hull.

We assume that packets arrive to each link l according to a stationary and ergodic process, and the average arrival rate is λ_l . The *capacity region* (or the *stability region*) under a given scheduling policy is defined as the set of arrival rate vectors $\vec{\lambda} = [\lambda_1, \lambda_2, \dots, \lambda_E]$ such that the system is stable (i.e., all queues are kept finite). It can be shown that the *optimal capacity region* Λ is given by [2], [18]–[20],

$$\Lambda = \left\{ \vec{\lambda} \mid \vec{\lambda} \preceq \vec{\phi}, \text{ for some } \vec{\phi} \in Co(\mathcal{M}_E) \right\}, \quad (1)$$

where $\vec{x} \preceq \vec{y}$ denotes that \vec{x} is component-wise dominated by \vec{y} . It is well-known that the *Maximal Weighted Matching (MWM)* policy can achieve this optimal capacity region under the node-exclusive interference model. However, its computational complexity ($O(N^3)$) is high. In this paper, we are interested in a suboptimal (but much simpler) policy called *Greedy Maximal Matching (GMM)*. *GMM* operates as follows: at each time-slot, it first picks the link l with the largest backlog; it then discards all links that interfere with link l ; it then picks the link with the largest backlog from the remaining links; and this process continues until no links are

left. As we discussed in the introduction, in this paper we are interested in characterizing the efficiency ratio of *GMM* under arbitrary network topologies. We formally define the notion of efficiency ratio as follows.

Definition 1: For a suboptimal scheduling policy, e.g., *GMM*, we say that it achieves a *fraction γ of the capacity region* under a given network topology if it can keep the system stable for any offered load $\vec{\lambda} \in \gamma\Lambda$.

Definition 2: The *efficiency ratio* γ^* of a scheduling policy under a given network topology is the supremum of all γ such that the policy can achieve a fraction γ of the capacity region, i.e.,

$$\gamma^* := \sup \{ \gamma \mid \text{the system is stable under all offered load vectors } \vec{\lambda} \text{ such that } \vec{\lambda} \preceq \gamma \vec{\phi} \text{ for some } \vec{\phi} \in Co(\mathcal{M}_E) \}. \quad (2)$$

III. AN EQUIVALENT CHARACTERIZATION OF THE EFFICIENCY RATIO OF *GMM*

In this section, we derive an equivalent characterization of the efficiency ratio of *GMM* under arbitrary network topologies. We first recall the following definition of *local pooling* from [15]:

Definition 3: Given a network graph $G(V, E)$, a set of links $L \subset E$ satisfies *local pooling*, if there exists a nonzero $\vec{\alpha} \in \mathbb{R}_+^{|L|}$ such that $\vec{\alpha}^T \vec{\phi}$ is a positive constant for all $\vec{\phi} \in Co(\mathcal{M}_L)$. The graph $G(V, E)$ satisfies *local pooling* if every $L \subset E$ satisfies local pooling.

An example of graphs that satisfy local pooling is a triangular network topology with three nodes and three links. In this graph, we have three maximal matchings; $[1, 0, 0]$, $[0, 1, 0]$, and $[0, 0, 1]$, where $[\cdot]$ represents a column vector. For any convex combination $\vec{\phi}$ of these three vectors, we have $\vec{\alpha}^T \vec{\phi} = 1$ with $\vec{\alpha} = [1, 1, 1]$.

Note that if a set of links L satisfies local pooling, no vector in $Co(\mathcal{M}_L)$ strictly dominates another vector in $Co(\mathcal{M}_L)$ ¹. Dimakis and Walrand [15] have shown that if a network graph satisfies local pooling, *GMM* achieves the full capacity region.

In this paper, we are interested in arbitrary network topologies that may not satisfy local pooling. We now generalize the notion of local pooling to that of the local-pooling factor.

Definition 4: A set of links L satisfies *σ -local pooling*, if $\sigma \vec{\mu} \not\prec \vec{\nu}$ for all $\vec{\mu}, \vec{\nu} \in Co(\mathcal{M}_L)$. In other words, for all $\vec{\mu}, \vec{\nu} \in Co(\mathcal{M}_L)$, there must exist some $k \in L$ such that $\sigma \mu_k < \nu_k$.

Note that if a graph, e.g., the triangular network topology, satisfies local pooling, then it must satisfy σ -local pooling for any $\sigma < 1$. We can prove this by contradiction. Suppose that there exist two convex combinations $\vec{\phi}_1, \vec{\phi}_2$ and $\sigma < 1$ such that $\sigma \vec{\phi}_1 - \vec{\phi}_2 \succeq \vec{0}$. Since the graph satisfies local pooling, there exists $\vec{\alpha}$ such that $\vec{\alpha}^T \vec{\phi}_1 = \vec{\alpha}^T \vec{\phi}_2 > 0$. Multiplying $\vec{\alpha}$ to both sides of $\sigma \vec{\phi}_1 - \vec{\phi}_2 \succeq \vec{0}$, we obtain $\sigma - 1 \geq 0$, which contradicts the assumption.

¹We can prove this by contradiction. Suppose that there exist $\vec{\phi}_1, \vec{\phi}_2 \in Co(\mathcal{M}_L)$ such that $\vec{\phi}_1 \succ \vec{\phi}_2$. Multiplying $\vec{\alpha}$ to both sides, we obtain $\vec{\alpha}^T \vec{\phi}_1 > \vec{\alpha}^T \vec{\phi}_2$, which contradicts the assumption.

Definition 5: The *local-pooling factor* of a graph $G(V, E)$ is the supremum of all σ such that every subset $L \in E$ satisfies σ -local pooling. In other words,

$$\begin{aligned} \sigma^* &:= \sup\{\sigma \mid \sigma \vec{\mu} \not\geq \vec{\nu} \text{ for all } L \text{ and all } \vec{\mu}, \vec{\nu} \in Co(\mathcal{M}_L)\} \\ &= \inf\{\sigma \mid \sigma \vec{\mu} \geq \vec{\nu} \text{ for some } L \text{ and some } \vec{\mu}, \vec{\nu} \in Co(\mathcal{M}_L)\}. \end{aligned}$$

By definition, if the local-pooling factor of a graph is σ^* , then every subset $L \subset E$ must satisfy σ^* -local pooling. Note that Definition 3 of local pooling corresponds to $\sigma^* = 1$. The results of [15] imply that if the local-pooling factor of the graph is 1, then the efficiency ratio of *GMM* will be 1. We next generalize this result to the case when $\sigma^* < 1$. We start with two lemmas.

Lemma 6: If the local-pooling factor of a graph $G(V, E)$ is σ^* , then the efficiency ratio γ^* of *GMM* under this network topology is no smaller than σ^* .

Proof: We need to show that for any offered load $\vec{\lambda}$ strictly within $\sigma^* \Lambda$, the network is stable under *GMM*. We prove stability by finding a Lyapunov function with negative drift for the fluid limit model of the system.

We first define the fluid limit model of the system as in [4], [21]. Let $A_l(t)$ denote the number of packets that arrive at link l at time-slot t and let $S_l(t)$ denote the number of packets that link l can serve at time-slot t . Let $Q_l(t)$ denote the number of packets queued at link l at the beginning of time-slot t . The queue length then evolves according to the following equation:

$$Q(t+1) = [Q_l(t) + A_l(t) - S_l(t)]^+,$$

where $[\cdot]^+$ denote the projection to non-negative real numbers. We can interpolate the values of $A_l(t)$ and $S_l(t)$ to all non-negative real number t by setting $A_l(t) = A_l(\lfloor t \rfloor)$ and $S_l(t) = S_l(\lfloor t \rfloor)$, where $\lfloor t \rfloor$ denotes the largest integer smaller than or equal to t . We also interpolate the values of $Q_l(t)$ by linear interpolation between $\lfloor t \rfloor$ and $\lfloor t \rfloor + 1$. Then, using the techniques of Theorem 4.1 of [21], we can show that, for almost all sample paths and for all positive sequence $x_n \rightarrow \infty$, there exists a subsequence x_{n_j} with $x_{n_j} \rightarrow \infty$ such that the following convergence holds uniformly over compact intervals of time t : For all $l \in E$,

$$\begin{aligned} \frac{1}{x_{n_j}} \int_0^{x_{n_j} t} A_l(s) ds &\rightarrow \lambda_l t, \\ \frac{1}{x_{n_j}} \int_0^{x_{n_j} t} S_l(s) ds &\rightarrow \int_0^t \pi_l(s) ds, \\ \frac{1}{x_{n_j}} Q_l(x_{n_j} t) &\rightarrow q_l(t). \end{aligned}$$

Moreover, for all $l \in E$, the limits $q_l(t)$ and $\pi_l(t)$ satisfy

$$\frac{d}{dt} q_l(t) = \begin{cases} \lambda_l - \pi_l(t), & \text{if } \lambda_l - \pi_l(t) \geq 0, \text{ or } q_l(t) > 0, \\ 0, & \text{otherwise,} \end{cases}$$

and $\pi_l(t)$ must satisfy the requirement of *GMM*. Any such limit $[q(t), \pi(t)]$ is called a *fluid limit* of the system.

We now use the idea from [15] and show that for any offered load λ strictly within $\sigma^* \Lambda$, the largest queue length of the fluid

limit model always decreases under *GMM*. Note that $q_l(t)$ is absolutely continuous, and hence its derivative exists almost everywhere. Consider those times t when the derivative $\frac{d}{dt} q_l(t)$ exists for all $l \in E$. Let $L_0(t)$ denote the set of links with the longest queue at time t , i.e.,

$$L_0(t) := \left\{ l \in E \mid q_l(t) = \max_{k \in E} q_k(t) \right\}.$$

Let $\bar{L}(t)$ denote the set of links with the largest derivative of the queue length among the links in $L_0(t)$,

$$\bar{L}(t) := \left\{ l \in L_0(t) \mid \frac{d}{dt} q_l(t) = \max_{k \in L_0(t)} \frac{d}{dt} q_k(t) \right\}.$$

Then, the links in $\bar{L}(t)$ will have the longest queue within a small time interval $(t, t + \delta]$. Hence, *GMM* will try to serve these links first. Let the service rate vector of *GMM* be $\vec{\pi}(t)$. Note that $\vec{\pi}(t)$ must be a convex combination of the maximal matchings on $\bar{L}(t)$, i.e., $\vec{\pi}(t) \in Co(\mathcal{M}_{\bar{L}(t)})$. Since the local-pooling factor is σ^* , and $\vec{\lambda}$ falls strictly within $\sigma^* \Lambda$, there must exist a $k \in \bar{L}(t)$ such that $\lambda_k < \pi_k(t)$.

Define

$$\epsilon_* := \inf_{\vec{\pi} \in Co(\mathcal{M}_L), L \subset E} \left\{ \max_{k \in L} (\pi_k - \lambda_k) \right\}. \quad (3)$$

Note that $\epsilon_* > 0$ since the local pooling factor is σ^* and $\vec{\lambda}$ falls strictly within $\sigma^* \Lambda$. Hence, by the earlier argument, there exists a $k \in \bar{L}(t)$ such that $\lambda_k - \pi_k(t) \leq -\epsilon_*$. This implies that $\frac{d}{dt} q_l(t) = \frac{d}{dt} q_k(t) \leq -\epsilon_*$ for all $l \in \bar{L}(t)$, i.e., the largest queue length must decrease in the time interval $(t, t + \delta]$.

Therefore, we can pick the Lyapunov function as $V(t) := \max_{l \in E} q_l(t)$. We have, if $V(t) > 0$,

$$\frac{D^+}{dt^+} V(t) \leq \max_{l \in L_0(t)} \frac{d}{dt} q_l(t) = \frac{d}{dt} q_k(t) \Big|_{k \in \bar{L}(t)} \leq -\epsilon_*,$$

where $\frac{D^+}{dt^+} V(t) = \lim_{\delta \downarrow 0} \frac{V(t+\delta) - V(t)}{\delta}$. Since this is true for almost every t , it implies that the fluid limit model of the system is stable. By Theorem 4.2 of [21], the original system is also stable. ■

Lemma 6 shows that the efficiency ratio of *GMM* under an arbitrary network graph is no smaller than the local-pooling factor, i.e., $\gamma^* \geq \sigma^*$.

The next lemma shows that $\gamma^* \leq \sigma^*$.

Lemma 7: If there exist a subset of links $L \subset E$, a positive number σ , and two vectors $\vec{\mu}, \vec{\nu} \in Co(\mathcal{M}_L)$ such that $\sigma \vec{\mu} \geq \vec{\nu}$, then, for arbitrarily small $\epsilon > 0$, there exists a traffic pattern with offered load $\vec{\nu} + \epsilon \vec{e}_L$ such that the system is unstable under *GMM*, where \vec{e}_L is a vector with $e_l = 1$ for $l \in L$ and $e_l = 0$ for $l \notin L$.

Remark: Since $\vec{\nu} \in \sigma \Lambda$, Lemma 7 implies that the efficiency ratio of *GMM* under this network topology is no greater than the local-pooling factor, i.e., $\gamma^* \leq \sigma^*$.

Proof: We provide the main ideas of the proof through an example. The full proof is provided in the extended version of the paper [22].

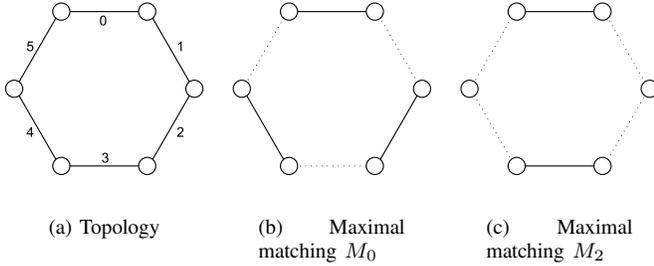


Fig. 1. The 6-link cycle network and the instances of maximal matching. The solid lines in (b) and (c) are the active links.

Consider the 6-link cycle network in Fig. 1. Number all links clockwise from 0 to 5. All possible maximal matchings under this network graph are listed below.

- $M_0 = [1, 0, 1, 0, 1, 0]$, $M_1 = [0, 1, 0, 1, 0, 1]$,
- $M_2 = [1, 0, 0, 1, 0, 0]$, $M_3 = [0, 0, 1, 0, 0, 1]$, $M_4 = [0, 1, 0, 0, 1, 0]$.

Note that the number of links included in a maximal matching is three for M_0 and M_1 , and is two for M_2 , M_3 , and M_4 . Figs. 1(b) and 1(c) show the two instances of the maximal matchings, i.e., M_0 and M_2 . Note that if we choose two vectors $\vec{\mu}, \vec{\nu}$ from the convex set of maximal matchings $Co(\{M_i\})$ as

$$\vec{\mu} = \frac{1}{2}M_0 + \frac{1}{2}M_1 = \left[\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2} \right]$$

$$\vec{\nu} = \frac{1}{3}M_2 + \frac{1}{3}M_3 + \frac{1}{3}M_4 = \left[\frac{1}{3}, \frac{1}{3}, \frac{1}{3}, \frac{1}{3}, \frac{1}{3}, \frac{1}{3} \right].$$

then $\frac{2}{3}\vec{\mu} \succeq \vec{\nu}$.

We now construct a traffic pattern with offered load $\vec{\lambda} = \vec{\nu} + \frac{\epsilon}{3}\vec{e}$ such that the system is unstable under *GMM*, where $\vec{e} = [1, 1, 1, 1, 1, 1]$ and ϵ is a small positive number. Assume that all queues in the system are of the same length at time 0.

- 1) *1st time-slot*: One packet is applied to links 0 and 3. Since *GMM* gives priority to links with a longer queue, it will serve links 0 and 3. Therefore, at the end of time-slot 1, all queues will still have the same length.
- 2) *2nd time-slot*: One packet is applied to links 1 and 4. For the same reason as above, *GMM* will serve links 1 and 4, and all queues will still have the same length at the end of time-slot 2.
- 3) *3rd time-slot*: With probability $1 - \epsilon$, one packet is applied to links 2 and 5. With probability ϵ , two packets are applied to links 2 and 5, and one packet is applied to all other links. In both cases, links 2 and 5 have the longest queue and will be served by *GMM*. At the end of time-slot 3, all queues still have the same length. However, with probability ϵ , the queue length increases by 1.

The pattern then repeats itself. Note that the key to this traffic pattern is (i) to keep all queues in L of the same length, and (ii) to inject packets according to the maximal matchings that

form the vector $\vec{\nu}$ so that these maximal matchings will be picked by *GMM*.

Over all links, the arrival rate is $\frac{1}{3} + \frac{\epsilon}{3}$ and the queue length increases by 1 with probability ϵ every three time-slots. Hence, the system with offered load $\vec{\nu} + \frac{\epsilon}{3}\vec{e}$ is unstable under *GMM*. ■

However, the optimal *MWM* policy can support the offered load $\vec{\mu} = \frac{2}{3}\vec{\nu}$ in this example. Hence, the efficiency ratio of *GMM* is no greater than $\frac{2}{3}$ in this 6-link cycle network.

From Lemmas 6 and 7, we can conclude that:

Proposition 8: The efficiency ratio γ^* of *GMM* under a given network topology is equal to its local-pooling factor σ^* .

This result provides an equivalent characterization of the efficiency ratio of *GMM* through the topological properties (i.e., the local-pooling factor) of the given graph. Unfortunately, it can still be quite difficult to compute the local-pooling factor for an arbitrary network graph. We next present some preliminary results for estimating the local-pooling factors.

IV. ESTIMATES OF THE LOCAL-POOLING FACTOR FOR ARBITRARY NETWORK GRAPHS

In this section, we would like to answer the following questions: (i) how do we estimate the local-pooling factor of a given graph? and (ii) what types of graphs will have low local-pooling factors? We now argue that both questions are intimately related to the characterization of the possible sets of unstable links. Note that in order to claim $\sigma^* \leq \sigma$, we must find a subset of links L , and two vectors $\vec{\mu}, \vec{\nu} \in Co(\mathcal{M}_L)$ such that $\sigma\vec{\mu} \succeq \vec{\nu}$. In fact, in the proof of Lemma 7, we show that for any $\epsilon > 0$, there exists a traffic pattern with offered load $\vec{\nu} + \epsilon\vec{e}_L$ such that the queues of all links in L increase to infinity together under *GMM*. Hence, a starting point to search for $\vec{\mu}$ and $\vec{\nu}$ would be to find out which subset of links L could have queue length increasing to infinity together under *GMM* at such an offered load $\vec{\lambda} \in \Lambda = \vec{\nu} + \epsilon\vec{e}_L$ and under such a traffic pattern. In this paper, we provide some preliminary results along this direction.

To avoid confusion, we let Y denote the set of links in E whose queue lengths increase to infinity together under *GMM* at offered load $\vec{\lambda} = \vec{\nu} + \epsilon\vec{e}_Y$, where $\vec{\nu} \in Co(\mathcal{M}_Y)$. By constructing the traffic pattern as in (1)-(3) earlier in the proof of Lemma 7, we have $Q_l(t) = 0$ for all $l \notin Y$, $Q_l(t) = Q(t)$ for all $l \in Y$, and $Q(t_k) \rightarrow \infty$ for a sequence $\{t_1, t_2, \dots, \infty\}$. We refer to the links in Y as the *unstable links*. Let X denote the set of nodes connected to any of the links in Y . We call the graph $U(X, Y)$ an *unstable subgraph* of $G(V, E)$. We next define the notion of an *isolated unstable link* and an *open unstable link* in the unstable subgraph $U(X, Y)$.

Definition 9: A link $l \in Y$ connecting two nodes n_1 and n_2 is an *isolated unstable link* if both n_1 and n_2 are of degree 1 in the unstable subgraph $U(X, Y)$.

Definition 10: A link $l \in Y$ connecting two nodes n_1 and n_2 is an *open unstable link* if either n_1 or n_2 is of degree 1 in the unstable subgraph $U(X, Y)$.

We have the following two results.

Lemma 11: If $\vec{\lambda} = \vec{v} + \epsilon \vec{e}_Y$ is strictly within Λ , then there is no isolated unstable link in Y under *GMM*.

Proof: Suppose that Y includes an isolated link l . By assumption, link l has no neighboring links in Y and should be included in all maximal matchings on Y . As a result, link l will be selected at all time-slots by *GMM*. Since $\lambda_l < 1$, the queue length of link l cannot increase to infinity. This contradicts the assumption that link l is unstable. ■

Lemma 12: If $\vec{\lambda} = \vec{v} + \epsilon \vec{e}_Y$ is strictly within Λ , there is no open unstable link in Y under *GMM*.

Proof: Suppose that Y includes an open unstable link $l_0 = (n_1, n_2)$. Without loss of generality, assume that node n_1 is shared by other unstable links $\{l_1, l_2, \dots, l_i\} \subset Y$, and node n_2 is of degree 1 in Y .

Note that every maximal matching on Y should include at least one of the links l_0, l_1, \dots, l_i ; because, if none of l_1, \dots, l_i is included, link l_0 should then be included in order for the matching to be maximal in Y . Hence, under *GMM*, the sum of the service rates over all of these links is 1 at all time-slots. Recall that all queues of links l_0, l_1, \dots, l_i are of the same length at $t = t_1, t_2, \dots$. Since $\sum_{k \in \{l_0, l_1, \dots, l_i\}} \lambda_k < 1$, these links cannot be unstable. This contradicts the assumption that the queues of these links increase to infinity together. ■

The above two lemmas imply that any link in Y must belong to a cycle formed by links in Y . Note that it immediately implies the result that *GMM* achieves the full capacity region in tree networks [15], [16].

In the following lemma, we characterize the property of the unstable subgraph when the arrival rate $\vec{\lambda}$ is within $\gamma\Lambda$.

Lemma 13: Suppose $\gamma \in (1/2, 1]$ and $\vec{\lambda} = \vec{v} + \epsilon \vec{e}_Y$ is strictly within $\gamma\Lambda$, then the degree of every node $v \in X$ in the unstable subgraph $U(X, Y)$ must be larger than $\frac{\gamma}{2\gamma-1}$.

Proof: We consider a node $n_0 \in X$ of degree d (in X) with neighbors $\{n_1, n_2, \dots, n_d\} \subset X$. Let l_i denote link (n_0, n_i) and let \mathcal{L}_i denote the set of unstable links connected to n_i , excluding l_i , i.e., $\mathcal{L}_i = Y \cap \mathcal{E}(n_i) \setminus \{l_i\}$, where $\mathcal{E}(n_i) \subset E$ is the set of links that are connected to node n_i .

Observe that all maximal matchings on Y must fall into one of the following two cases:

- 1) A maximal matching on Y includes a link l_i . In this case, we say that node n_0 is black (see Fig. 2(a)).
- 2) A maximal matching on Y includes a link from each \mathcal{L}_i . In this case, we say that node n_0 is white (see Fig. 2(b)).

We first show that the fraction of time that n_0 is black (the first case) is no more than γ . Let $\lambda_n := \sum_{l \in \mathcal{E}(n)} \lambda_l$ denote the arrival rate at node n , and let $D_n := \sum_{l \in \mathcal{E}(n)} D_l$ denote the departure rate at node n , where D_l is the departure rate at link l . Note that the optimal capacity region Λ is bounded by

$$\Lambda \subset \Psi := \left\{ \vec{\lambda} \mid \sum_{l \in \mathcal{E}(n)} \lambda_l \leq 1, \text{ for all } n \in E \right\}.$$

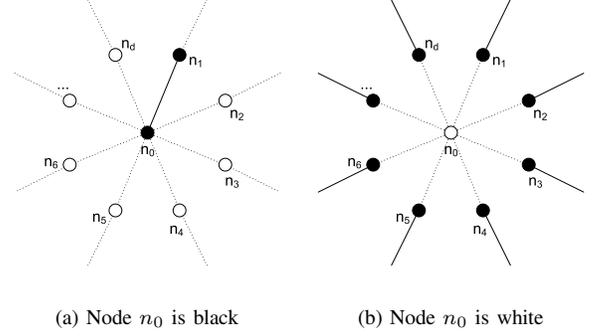


Fig. 2. Maximal matchings on an unstable network with a degree- d node n_0 .

By assumption $\vec{\lambda} \in \gamma\Lambda$, we have

$$\sum_{l \in \mathcal{E}(n_0) \cap Y} \lambda_l \leq \sum_{l \in \mathcal{E}(n_0)} \lambda_l = \lambda_{n_0} \leq \gamma. \quad (4)$$

If the fraction of time that n_0 is black is greater than γ , then the arrival rate at node n_0 will be smaller than the service rate at n_0 , which implies that the queues at the links incident to node n_0 cannot increase to infinity together. This contradicts our assumption.

We next count the total service rates over all nodes n_0, n_1, \dots, n_d . Let β denote the fraction of time that node n_0 is black, $0 \leq \beta \leq \gamma$. If node n_0 is black, then at least two nodes (one is n_0) are served. If node n_0 is white, then nodes $\{n_1, n_2, \dots, n_d\}$ are served. Hence, we have

$$\sum_{k=0}^d D_{n_k} \geq 2\beta + d(1-\beta) \geq 2\gamma + d(1-\gamma). \quad (5)$$

In the last inequality, we have used $0 \leq \beta \leq \gamma$ and $d \geq 2$ (by Lemma 12).

Using the assumption that $\vec{\lambda}$ falls strictly in $\gamma\Psi$, we have

$$\sum_{k=0}^d \lambda_{n_k} < \gamma(d+1). \quad (6)$$

We must have

$$\sum_{k=0}^d D_{n_k} \leq \sum_{k=0}^d \lambda_{n_k}, \quad (7)$$

since, otherwise, the queue lengths of these links cannot increase to infinity together. Combining (5), (6), and (7), we obtain

$$d > \frac{\gamma}{2\gamma-1}. \quad (8)$$

■

The above lemma immediately implies the second main result of the paper.

Proposition 14: For a given network graph $G(V, E)$ where the largest node degree is d^* , the efficiency ratio γ^* of *GMM* must be no smaller than $\frac{d^*}{2d^*-1}$.

Proof: Suppose that the efficiency ratio is smaller than

$\frac{d^*}{2d^*-1}$. Then, according to Proposition 8, we have $\sigma^* < \frac{d^*}{2d^*-1}$. Hence, from Definition 5, there must exist a subset $L \subset E$ and $\vec{\mu}, \vec{\nu} \in \mathcal{C}o(\mathcal{M}_L)$ such that $\sigma\vec{\mu} \geq \vec{\nu}$ for some $\sigma < \frac{d^*}{2d^*-1}$. Using Lemma 7, there exists a traffic pattern with $\vec{\lambda} = \vec{\nu} + \epsilon\vec{e}_L$, such that the queue lengths of links in L increase to infinity together. By choosing ϵ small, we can have $\vec{\lambda}$ fall strictly in $\frac{d^*}{2d^*-1}\Lambda$. Then, using Lemma 13, the degree of every node in the unstable graph must be larger than d^* . This contradicts the assumption that the largest node-degree is d^* . ■

According to Proposition 14, in order to find network topologies where the efficiency ratio of *GMM* is low, we must look at those graphs where the maximum node-degree is high. We have been able to find such graphs where the bound in Proposition 14 is tight with² $d^* = 2$. Recall the 6-link cycle network shown in the proof of Lemma 7. We have already shown that this graph has $\gamma^* \leq \frac{2}{3}$. On the other hand, since this graph has a maximum node-degree of two, Lemma 13 implies that $\gamma^* \geq \frac{2}{3}$. Therefore, *GMM* has an efficiency ratio $\gamma^* = \frac{2}{3}$ in the 6-link cycle network. To the best of our knowledge, *this is the first result that provides the exact efficiency ratio for a network graph where GMM cannot achieve the full capacity region.*

V. CONCLUSION

In this paper, we have provided new analytical results on the achievable performance of *GMM* for a large class of network topologies. We derive our results via a topological approach that extends the recently developed notion of local pooling to a more general topological notion called σ -local pooling, and a corresponding notion called local-pooling factor. We show that for a given graph, the efficiency ratio of *GMM* is equal to its local-pooling factor. Thus, we are able to focus on the topological property of graphs to obtain the achievable performance of *GMM*. However, it turns out that estimating the local-pooling factor is non-trivial, and may require high complexity for arbitrary network topologies. Nonetheless, by studying the properties of unstable networks, we are able to provide preliminary results on estimating the local-pooling factor of arbitrary network topologies. In particular, we show that the local-pooling factor (and hence the efficiency ratio γ^* of *GMM*) of a graph with maximum node degree d^* is no smaller than $d^*/(2d^* - 1)$. The tightness of the bound is demonstrated through the 6-link cycle topology, where $d^* = 2$.

There remain many interesting open problems in these directions. For example, further research on the topological properties of graphs could result in a better estimate of the performance limits. We also expect that different interference models will affect the capacity region of *GMM*. While our results on the relationship between the performance of *GMM* and the local-pooling factor remain the same for a more general class of interference models, more work needs to be done to evaluate the local-pooling factor for general interference models. Finally, the authors of [15] show that, if

²We also found a network graph where the bound is tight with $d^* = 3$. We refer interested readers to [22].

the arrivals satisfy certain randomness property, *GMM* may achieve the full capacity region even if the network graph does not satisfy local pooling. It would be interesting to study whether the results in this paper can be improved under similar assumptions.

REFERENCES

- [1] X. Lin and N. B. Shroff, "The Impact of Imperfect Scheduling on Cross-Layer Congestion Control in Wireless Networks," *IEEE/ACM Transactions on Networking*, vol. 14, no. 2, pp. 302–315, April 2006.
- [2] L. Tassiulas and A. Ephremides, "Stability Properties of Constrained Queueing Systems and Scheduling Policies for Maximal Throughput in Multihop Radio Networks," *IEEE Transactions on Automatic Control*, vol. 37, no. 12, pp. 1936–1948, December 1992.
- [3] C. Joo and N. B. Shroff, "Performance of Random Access Scheduling Schemes in Multi-hop Wireless Networks," in *IEEE INFOCOM*, May 2007.
- [4] X. Lin and S. Rasool, "Constant-Time Distributed Scheduling Policies for Ad Hoc Wireless Networks," in *IEEE CDC*, December 2006.
- [5] L. Tassiulas, "Linear Complexity Algorithms for Maximum Throughput in Radio Networks and Input Queued Switches," in *IEEE INFOCOM*, April 1998.
- [6] S. Ray and S. Sarkar, "Arbitrary Throughput Versus Complexity Trade-offs in Wireless Networks using Graph Partitioning," in the *Information Theory and Applications Second Workshop*, January 2007.
- [7] G. Sharma, C. Joo, and N. B. Shroff, "Distributed Scheduling Schemes for Throughput Guarantees in Wireless Networks," in the *44th Annual Allerton Conference on Communications, Control, and Computing*, September 2006.
- [8] A. Gupta, X. Lin, and R. Srikant, "Low-Complexity Distributed Scheduling Algorithms for Wireless Networks," in *IEEE INFOCOM*, May 2007.
- [9] E. Modiano, D. Shah, and G. Zussman, "Maximizing Throughput in Wireless Networks via Gossiping," *Sigmetrics Performance Evaluation Review*, vol. 34, no. 1, pp. 27–38, 2006.
- [10] B. Hajek and G. Sasaki, "Link Scheduling in Polynomial Time," *IEEE Transactions on Information Theory*, vol. 34, no. 5, September 1988.
- [11] S. Sarkar and L. Tassiulas, "End-to-end Bandwidth Guarantees Through Fair Local Spectrum Share in Wireless Ad-hoc Networks," in *IEEE CDC*, December 2003.
- [12] C. H. Papadimitriou and K. Steiglitz, *Combinatorial Optimization: Algorithms and Complexity*. Prentice-Hall, 1982.
- [13] E. Leonardi, M. Mellia, F. Neri, and M. A. Marsan, "On the Stability of Input-Queued Switches with Speed-Up," *IEEE/ACM Transactions on Networking*, vol. 9, no. 1, February 2001.
- [14] N. McKeown, "Scheduling Algorithms for Input-Queued Cell Switches," Ph.D. dissertation, University of California at Berkeley, 1995.
- [15] A. Dimakis and J. Walrand, "Sufficient Conditions for Stability of Longest-Queue-First Scheduling: Second-order Properties using Fluid Limits," *Advances in Applied Probability*, vol. 38, no. 2, pp. 505–521, 2006.
- [16] A. Brzezinski, G. Zussman, and E. Modiano, "Enabling Distributed Throughput Maximization in Wireless Mesh Networks: A Partitioning Approach," in *ACM Mobicom*. New York, NY, USA: ACM Press, 2006, pp. 26–37.
- [17] J.-H. Heopman, "Simple Distributed Weighted Matchings," eprint, October 2004. [Online]. Available: <http://arxiv.org/abs/cs/0410047>
- [18] M. J. Neely, E. Modiano, and C. E. Rohrs, "Power Allocation and Routing in Multibeam Satellites with Time-varying Channels," *IEEE/ACM Transactions on Networking*, vol. 11, no. 1, pp. 138–152, 2003.
- [19] A. Eryilmaz, R. Srikant, and J. Perkins, "Stable Scheduling Policies for Fading Wireless Channels," *IEEE/ACM Transactions on Networking*, vol. 13, no. 2, pp. 411–424, April 2005.
- [20] R. L. Cruz and A. V. Santhanam, "Optimal Routing, Link Scheduling and Power Control in Multi-hop Wireless Networks," in *IEEE INFOCOM*, San Francisco, April 2003.
- [21] J. G. Dai, "On Positive Harris Recurrence of Multiclass Queueing Networks: A Unified Approach via Fluid Limit Models," *Annals of Applied Probability*, vol. 5, no. 1, pp. 49–77, 1995.
- [22] C. Joo, X. Lin, and N. B. Shroff, "Performance Limits of Greedy Maximal Matching in Multi-hop Wireless Networks," Purdue University, Tech. Rep., 2007. [Online]. Available: <http://netlab.snu.ac.kr/~cjoo>