Delay-Constrained Topology-Transparent Distributed Scheduling for MANETs

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***Abstract*—Transparent topology is common in many mobile ad hoc networks (MANETs) such as vehicle ad hoc networks (VANETs), unmanned aerial vehicle (UAV) ad hoc networks, and wireless sensor networks due to their decentralization and mobility nature. There are many existing works on distributed scheduling scheme design for topology-transparent MANETs. Most of them focus on delay-unconstrained settings. However, with the proliferation of real-time applications over wireless communications, it becomes more and more important to support delay-constrained traffic in MANETs. In such applications, each packet has a given hard deadline: if it is not delivered before its deadline, its validity will expire and it will be removed from the system. This feature is fundamentally different from the traditional delay-unconstrained one. In this paper, we for the first time investigate distributed scheduling schemes for a topology-transparent MANET to support delay-constrained traffic. We analyze and compare probabilistic ALOHA scheme and deterministic sequence schemes, including the conventional time division multiple access (TDMA), the Galois field (GF) sequence scheme proposed in [1], and the combination sequence scheme that we propose for a special type of sparse network topology. We use both theoretical analysis and empirical simulations to compare all these schemes and summarize the conditions under which different individual schemes perform best.**

I. Introduction

An ad hoc network is *topology-transparent* if the network topology is unknown to all network nodes. Many mobile ad hoc networks (MANETs) have transparent topologies since it is difficult or infeasible for individual nodes to acquire global network connection information in real time, especially in the case of no centralized controller. For example, network nodes in a vehicle ad hoc network (VANET) or an unmanned aerial vehicle (UAV) ad hoc network move over time and thus the network topology changes over time; it is costly for sensor nodes in a large-scale wireless sensor network to obtain the whole network topology due to its large scale. How to perform distributed scheduling to deliver packets under the topology-transparent setting has become a vital research direction.

There are many solutions on this topic, including probabilistic schemes and deterministic schemes. One conventional probabilistic scheme is slotted ALOHA where each node transmits its packet at any slot with a common probability. For deterministic scheme, time division multiple access (TDMA), where each node is assigned a unique slot to transmit, is a common option. A variety of more sophisticated topology-transparent sequence schemes have been proposed in the literature; see the survey paper [2] and the references therein. Such schemes usually take into account the *network density* D (maximum number of interfering nodes among all nodes in the network). They include algebraic approaches based on properties of Galois field (GF) [1], [3], combinatorial approaches based on combinatorial structures like orthogonal arrays and Steiner systems [4], [5], and number-theoretic approaches based on Chinese remainder theorem [6], [7], etc. Among them, the GF sequence scheme [1] is the most common one.

Most existing approaches for topology-transparent distributed scheduling focus on delay-unconstrained traffic where a packet can be kept in the queue for however much time. However, with the proliferation of real-time applications over wireless communications, MANETs nowadays need to support more and more delay-constrained traffic. Typical examples include multimedia wireless transmission system such as real-time streaming and video conferencing via cellular or WiFi networks, wireless cyber-physical systems (CPSs) such as factory automation via wireless communications [8], and networked control systems (NCSs) such as remote control (via wireless communications) of UAVs [9]. In these applications, each packet has a *given* hard deadline: if it is not delivered before its deadline, it expires and will be removed from the system. This feature is fundamentally different from the traditional delay-unconstrained one. There are many existing research works on delay-constrained wireless communications where the major performance metric is *timely throughput*, which is usually defined as the ratio of the number of packets that have been delivered before expiration to the number of all generated packets [8], [10]–[12]. The concept of timely throughput is also closely related to *reliability*, which is a major performance metric in ultra-reliable low latency communications (URLLC) in 5G [13]–[16]. However, those existing works only focus on networks with known (instead of transparent) topologies.

To the best of our knowledge, designing topology-transparent distributed scheduling schemes to support delay-constrained traffic in an MANET remains an open question. In this work, this problem is investigated for the first time. We use both theoretical analysis and empirical simulations to study probabilistic ALOHA scheme and three deterministic sequence schemes under the delay-constrained setting. The sequence schemes include *TDMA* and *the GF sequence scheme* [1] for general network density D, and *the combination sequence scheme* for a special type of sparse network topology with $D = 1$. Our main contributions of this work is to compare these schemes both theoretically and empirically and summarize the conditions under which different individual schemes outperform others.

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Due to the page limit, we have moved most of technical proofs and some supplementary materials into our technical report [17].

II. System Model

Network Topology. We consider an MANET with N transmitters and N receivers (both indexed from 1 to N) which are geographically distributed in an area. A transmitter can transmit packets (or cause interference) to a receiver if their distance is less than or equal to $\Delta > 0$, which is called the communication range. In our work, we assume that transmitter $i \in \{1, 2, \cdots, N\}$ only needs to send information to receiver i; they form a pair, called pair i. One practical example is a VANET where multiple vehicle-to-vehicle pairs need to share data simultaneously [18]–[24]. Another practical example of our model is that individual controllers send control messages to their own UAVs via a shared wireless communication channel [25]. In addition, our model can also be applied to D2D networks where multiple D2D pairs share the same wireless channel to transmit data [26]–[28].

In addition, transmitter i causes interference to receiver $j \neq i$ if their distance is within the communication range Δ. In this case, we call transmitter i an *interferer* of receiver j. Otherwise, if their distance is larger than Δ, transmitter i is not an interferer of receiver j. Our channel model is an *unreliable collision channel*. If both transmitter i and any one or more interferers of receiver i transmit a packet simultaneously, collision happens and no packets of them can be delivered. Even without collision, receiver i can successfully receive a packet of transmitter i with probability $p_i \in (0, 1]$ if transmitter i transmits a packet. The successful probability p_i models the unreliability of wireless transmission due to shadowing and fading. The successful probabilities could be different for different pairs (i.e., p_i depends on i) due to heterogeneous channel qualities. The network topology can change over time arbitrarily but satisfies the following two conditions:

(i) For any $i \in \{1, 2, \cdots, N\}$, the distance between transmitter i and receiver i is always within Δ;
(ii) At any time and at any location, there are no more than $D + 1$ transmitters in any circle of radius Δ, where D is a non-negative integer.

Condition (i) shows that transmitter i always establishes connection to receiver i. Condition (ii) is the density assumption of the network topology, which means that any receiver can have at most D interferers at any time excluding its own intended transmitter. We also call D the *network density* of the network topology. Note that D is not necessarily equal to $N-1$. When the transmitters are distributed sparsely, D can be far less than $N-1$. In particular, when $D = 0$, meaning that all transmitters are distributed extremely sparsely, all receivers do not have any interferer and thus all transmitters can transmit simultaneously without any collision. To avoid such triviality, we assume that $D \geq 1$ in the rest of this paper.

The network topology is *transparent* in the sense that all transmitters do not know the exact network topology but only the density D. Furthermore, we assume that there is *no feedback* from the receiver to the transmitter about whether the transmitted packet is delivered successfully or not.

Delay-Constrained Traffic Pattern. We consider a time-slotted system (indexed from slot 1) in which all nodes are time synchronized with no propagation delay. We assume that the hard deadline of all packets in the system is T slots, which is specified by the application. In general, the scheduling design and the system performance are greatly influenced by the traffic pattern under the delay-constrained setting [8]. In this work, as a first attempt to investigate the topology-transparent distributed scheduling under the delay-constrained setting, we consider a simple yet common frame-synchronized traffic pattern [8], [10], [29], which can find applications in CPSs [30] and NCSs [31] where a system generates the control packets/messsages periodically. Starting from slot 1, every T consecutive slots is called a frame, indexed from frame 1. Therefore, frame k consists of slot $(k-1)T+1$ to slot kT. We also call the application-specified hard deadline T the *frame length*. Each of the N transmitters generates a packet at the beginning of a frame, which will become expired and be removed from the system at the end of the frame. Consider the example of UAVs. Each controller (transmitter) needs to send control messages to its controlled UAV periodically, and the period is T slots. All the controllers' clocks are synchronized so that the starting time and the period are the same in all the controllers. This is an example for frame-synchronized traffic pattern. In addition, following [8], [10], [32], we investigate the delay-constrained topology-transparent scheduling problem beginning with this special frame-synchronized traffic pattern. In our technical report [17], we also evaluate the performance of the proposed schemes under a poisson-arrival traffic pattern.

The timely throughput of pair i is defined as,

$$R_i \triangleq \lim_{k \to \infty} \frac{\mathbb{E}\left[\substack{\text{number of pair-}i\text{ packets delivered before} \\ \text{expiration from slot 1 to slot } kT}\right]}{k}, \tag{1}$$

which only counts those packets that have been delivered before expiration [8], [10].

Since there is one and only one new packet arrival in every frame, (1) implies that the *timely throughput* of pair i, i.e., R_i, is the ratio of the expected number of packets that have been delivered before expiration to the number of all generated packets of transmitter i. Clearly, the maximum value of R_i is 1. In addition, the timely throughput defined in (1) is the average probability that a pair-i packet is delivered successfully before expiration. Thus, it measures the reliability of pair i, which is a major performance metric in URLLC in 5G [13]–[16]. Furthermore, we note that R_i depends on the scheduling policy which will be explained next.

Distributed Scheduling. Our goal is to design a distributed scheduling policy satisfying all aforementioned assumptions to maximize the average system timely throughput, i.e.,

$$\max_{\pi \in \Pi} \quad \frac{\sum_{i=1}^{N} R_i^{\pi}}{N}, \tag{2}$$

where Π is the set of all distributed scheduling policies and R_i^{π} is the achieved timely throughput of pair i under policy π. The policy is distributed in the sense that each transmitter needs to determine its own transmission strategy without the coordination of a centralized controller.

It is difficult to design the optimal distributed scheduling policy, i.e., solving (2) optimally. In this work, we consider two popular types of distributed scheduling schemes: *probabilistic ALOHA scheme* and *deterministic sequence schemes*. Since the probabilistic ALOHA scheme is relatively easy to design and analyze and due to the page limit, we move the details into out technical report [17]. We use $\underline{R}^{\mathsf{ALOHA}^*}(D, N, T)$ (see Equ. (6) in [17]) to denote the lower bound of the achieved average system timely throughput under the probabilistic ALOHA scheme for given parameters D, N, and T. In the following, we detail deterministic sequence schemes.

III. Deterministic Sequence Schemes

In sequence schemes, we pre-assign any transmitter i a binary sequence $\boldsymbol{S}_i = (S_i(1), S_i(2), \cdots)$ with the convention that $S_i(t) = 1$ means that transmitter i will transmit its packet at slot t and $S_i(t) = 0$ means that it will remain idle at slot t. Thus, following the assigned sequence, each transmitter will either transmit or not in any slot. The sequence schemes are distributed in the sense that there is no need to involve a centralized controller once the sequences are assigned to transmitters. They are deterministic schemes in contrast to the probabilistic ALOHA scheme. We remark that in the sequence-based schemes, a preliminary is to perform sequence allocation. A common solution is to pre-assign sequences for users, which needs to know the total number of pairs, i.e., N, in advance. We use this approach in our paper. For example, consider N pairs of UAVs and controllers. Before they perform task by forming an MANET, we pre-assign each pair a sequence according to our sequence scheme. Once the sequences are assigned to pairs, each transmitter can work distributedly according to its assigned sequence. A more practical solution is to automatically allocate sequences relying on some extra knowledge. For example, reference [33] describes a method that a user can automatically get a sequence based on its geographic location. Reference [34] introduces an allocation method for VANET with the help of roadside nodes or roadside units near highway entrances or toll booths.

If in slot t, $S_i(t) = 1$ and $S_j(t) = 0$ for any interferer j of receiver i, we call such a t a *collision-free slot* of transmitter i (or sequence $\boldsymbol{S}_i$). A packet of transmitter i can be delivered successfully with probability p_i in those collision-free slots and no successful delivery happens in other slots. Note that for a given sequence scheme, whether slot t is a collision-free slot of transmitter i depends on the network topology. Since the traffic pattern is fixed, the pair i's timely throughput is determined by the set of all collision-free slots of transmitter i.

In general, the sequence could be in an arbitrary form and of an infinite-dimension design space. However, in our work, due to the periodical nature of the traffic pattern, we only consider *periodic* sequences in order to simplify the design. Specifically, a periodic sequence $\boldsymbol{S} = (S(1), S(2), \cdots)$ with period L satisfies $S(t) = S(t-L), \forall t > L$, i.e., $\boldsymbol{S} = (S(1), S(2), \cdots, S(L), S(1), S(2), \cdots, S(L), \cdots)$. Thus, a periodic sequence with period L is completely determined by its first L elements. We then represent a periodic sequence with period L by a sequence of finite length L, i.e., $\boldsymbol{S} = (S(1), S(2), \cdots, S(L))$. For a sequence of period L, starting from the first period, every T periods is called a super period (of in total TL slots), indexed from super period 1. Clearly, super period k is from period $(k-1)T+1$ to period kT. We establish the following result.

***Theorem** 1:* If the sequence of transmitter i is of period L and the set of its collision-free slots in any super period $k \in \{1, 2, \cdots\}$ is $\{t_k + (k-1)TL + mL : m = 0, 1, \cdots, T-1, 1 \le t_k \le L\}$, then the following results hold.

- Case 1: If $L \ge T$, the timely throughput of pair i is

$$R_i^{\text{Case-1}}(L,T) = \frac{T}{L} \cdot p_i. \tag{3}$$

- Case 2: If $L < T$, the timely throughput of pair i is

$$R_i^{\text{Case-2}}(L,T) = \frac{\alpha\left[1-(1-p_i)^{\left\lceil \frac{T}{L} \right\rceil}\right] + \beta\left[1-(1-p_i)^{\left\lfloor \frac{T}{L} \right\rfloor}\right]}{L}, \tag{4}$$

where $\alpha = (T \bmod L)$ and $\beta = L - \alpha$.

The condition for the sequence in Theorem 1 means that there is *exactly* one collision-free slot in any period of any super period and its location has the same offset relative to the beginning of the period but the offset, i.e., t_k, could be different for different super periods. For simplicity, we call it *location-fixed condition*. Theorem 1 shows that if a sequence satisfies the location-fixed condition, we can use (3) and (4) to obtain the exact timely throughput. In addition, if the set of collision-free slots of a sequence in any super frame k includes some extra slots in addition to $\{t_k + (k-1)TL + mL : m = 0, 1, \cdots, L-1\}$, we can use (3) and (4) to obtain a lower bound of the timely throughput.

In the special case of $p_i = 1$, every packet of transmitter i will be delivered successfully with certainty if no interferer of receiver i transmits simultaneously. This special case is called the *perfect-channel case*. It is straightforward to see that when $p_i = 1$, (4) becomes $R_i^{\text{Case-2}}(L,T) = 1$. This means that pair i achieves its maximum value 1 where the sequence period L is not greater than the frame length T. Therefore, one direction to find best sequences in the perfect-channel case is to find a sequence set of period L such that each one has (at least) one collision-free-slot in a period subject to the topology density constraint D. In addition, we should try to minimize the sequence period L such that $L \le T$. For the imperfect-channel case, i.e., $p_i \in (0,1)$, we also provide a reason to minimize the sequence period L.

***Lemma** 1:* $R_i^{\text{case-1}}(L,T)$ in (3) strictly decreases as L increases. When $p_i = 1$, $R_i^{\text{case-2}}(L,T)$ in (4) remains to be constant 1 for all $L \le T$. When $p_i \in (0,1)$, $R_i^{\text{case-2}}(L,T)$ in (4) strictly decreases as L increases.

Lemma 1 shows that if we can find a sequence set assigned to N transmitters such that each sequence has one collision-free slot in a period and satisfies the location-fixed condition, we should try to minimize the sequence period L to increase the average system timely throughput.

We will next introduce three types of sequence schemes. The first one is the conventional TDMA scheme, which guarantees that each transmitter/sequence has exactly one collision-free slot in a period for any network topology. The second one is the GF topology-transparent scheduling sequence scheme proposed in [1]. For simplicity, we call it *the GF sequence scheme*. It guarantees at least one collision-free slot for each transmitter/sequence in a period for any network topology with density D. The last one is called *the combination sequence scheme* designed for the special case of $D = 1$. It is "optimal" in the sense that it finds the minimal sequence period L such that each sequence has at least one collision-free slot in a period for any network topology with density $D = 1$.

A. TDMA

The simplest sequence scheme is the conventional TDMA scheme where we assign the transmission token in a round-robin manner. Specifically, the sequence period is $L = N$ and the sequence for transmitter i, i.e., $\boldsymbol{S}_i$, satisfies

$$S_i(t) = \begin{cases} 1, & \text{if } t = i; \\ 0, & \text{otherwise.} \end{cases} \quad \forall t = 1, 2, \cdots, N. \tag{5}$$

The TDMA scheme guarantees that each transmitter has exactly one collision-free slot within a period $L = N$ for any network topology and any sequence $\boldsymbol{S}_i$ satisfies the location-fixed condition. Then according to Theorem 1, if $N \ge T$, the timely throughput of transmitter i is $R_i^{\text{case-1}}(N,T)$ and the average system timely throughput is

$$R^{\text{TDMA-1}}(N,T) = \frac{\sum_{i=1}^{N} R_i^{\text{case-1}}(N,T)}{N}. \tag{6}$$

If $N < T$, the timely throughput of transmitter i is $R_i^{\text{case-2}}(N,T)$ and the average system timely throughput is

$$R^{\text{TDMA-2}}(N,T) = \frac{\sum_{i=1}^{N} R_i^{\text{case-2}}(N,T)}{N}. \tag{7}$$

Note that in TDMA, we guarantee that a sequence will not be blocked[1] by all other $N-1$ sequences, regardless of the network topology. Thus, the results in (6) and (7) hold for any network topology with any network density D which could change in any slot.

B. The GF Sequence Scheme

Different from TDMA, the GF sequence scheme proposed in [1] can exploit the sparsity of the network topology, which guarantees that any sequence will not be blocked by any other D sequences. In the GF sequence scheme, a sequence period consists of q sub-periods each of which is of length q, where q is a prime power. Thus, the sequence period is $L = q^2$. The construction of a sequence is as follows. Each transmitter $i \in \{1, 2, \ldots, N\}$ is assigned a sequence according to a unique polynomial $f_i(e)$ of degree at most k (where k is a nonnegative integer) over Galois field $GF(q)$. We index the elements of $GF(q)$ from 1 to q and the x-th element is denoted by e_x. The value $f_i(e_x)$ determines the transmission slot for transmitter i in the x-th sub-period in the following manner: if the value of $f_i(e_x) = e_y$, i.e., the y-th element in $GF(q)$, we set the y-th slot in the x-th sub-period to be 1 and set other slots to be 0.

Within a period, the number of 1s of each transmitter is q since each sub-period contains exactly one 1. The number of conflicting 1s for any two transmitters within a period is at most k due to the following fact: for any two polynomials of degree at most k over $GF(q)$, their difference has at most k roots. Thus as long as $q - kD \geq 1$, any sequence will not be blocked by any other D sequences and thus any transmitter can be guaranteed to have at least one collision-free slot.

The total number of polynomials with degree at most k over $GF(q)$ is q^{k+1}. Then as long as $q^{k+1} \geq N$, we can guarantee that each transmitter can get a unique polynomial and thus a unique sequence. Therefore, to minimize the sequence period $L = q^2$, for given N and D, we need to find the smallest prime power q to satisfy

$$\begin{cases} q - kD \geq 1, \\ q^{k+1} \geq N. \end{cases} \tag{8}$$

The smallest prime power q satisfying (8) is denoted by $q(D,N)$ and the corresponding sequence period is $L = q^2(D,N)$. We give an example for GF sequence in our technical report [17].

When the network topology changes slowly in the sense that the topology is fixed in any super period, any GF sequence has *at least* one collision-free slot in any period and the offsets are the same in all periods in a super period. Thus, the GF sequence scheme satisfies the location-fixed location possibly with some extra collision-free slots in the slowly-changing topology scenario. Then according to Theorem 1, the timely throughput of pair i is lower bounded by $R_i^{\text{case-1}}(q^2(D,N),T)$ when $q^2(D,N) \geq T$ and is lower bounded by $R_i^{\text{case-2}}(q^2(D,N),T)$ when $q^2(D,N) < T$. Thus, if the network topology does not change in any super period, in the case of $q^2(D,N) \geq T$, the average system timely throughput is lower bounded by

$$\underline{R}^{\text{GF-1}}(D,N,T) = \frac{\sum_{i=1}^{N} R_i^{\text{case-1}}(q^2(D,N),T)}{N}; \tag{9}$$

in the case of $q^2(D,N) < T$, the average system timely throughput is lower bounded by

$$\underline{R}^{\text{GF-2}}(D,N,T) = \frac{\sum_{i=1}^{N} R_i^{\text{case-2}}(q^2(D,N),T)}{N}. \tag{10}$$

C. The "Optimal" Combination Sequence Scheme for $D = 1$

In the sequence scheme design, there is an interesting and important combinatorial problem: what is the minimum length of the sequences such that there exists a set of at least N sequences each of which has at least one collision-free slot for any network topology with density D? We denote such minimum length by $L^{\min}(D,N)$. For $D = 1$, we can explicitly characterize $L^{\min}(1,N)$. We construct the sequence set according to all combinations of $L^{\min}(1,N)$ choosing $\left\lceil \frac{L^{\min}(1,N)}{2} \right\rceil$, and then arbitrarily select N sequences and assign them to N pairs. This is the combination sequence scheme. Due to the page limit, we move details of the combination sequence scheme to our technical report [17].

IV. Theoretical Comparison

A. Comparison between ALOHA and TDMA

First, we analyze the lower bound of the average system timely throughput of ALOHA.

Theorem 2: $\underline{R}^{\text{ALOHA}^*}(D,N,T)$ is strictly decreasing with respect to D.

To compare ALOHA and TDMA, recall that the average system timely throughput of TDMA does not vary with respect to D. Thus, we can find a smallest density D (denoted as D^*) such that $\underline{R}^{\text{ALOHA}^*}(D,N,T) \geq R^{\text{TDMA-1}}(N,T)$ when $N \geq T$ or $\underline{R}^{\text{ALOHA}^*}(D,N,T) \geq R^{\text{TDMA-2}}(N,T)$ when $N < T$. Therefore, according to Theorem 2, it follows that ALOHA has larger average system timely throughput than TDMA when $D \leq D^*$. In addition, such a D^* can be found by an efficient binary-search scheme. We take the convention that $D^* = -\infty$ if we cannot find such a D, which means that TDMA is better than the lower bound of ALOHA for all $D \geq 1$.

B. Comparison between the GF Sequence Scheme and TDMA

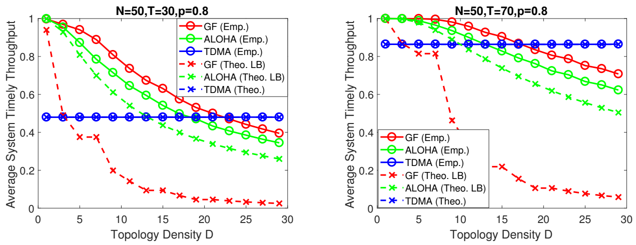
In the GF sequence scheme, the sequence period is $L = q^2(D,N)$. We first establish the following result.

Lemma 2: In the GF sequence scheme, $L = q^2(D,N)$ is non-decreasing with respect to D.

Proof: For each D, we find the smallest prime power q satisfying (8), i.e., $q(D,N)$. The result follows from the fact that the prime power q satisfying (8) with density D also satisfies (8) with any density $D' < D$. ■

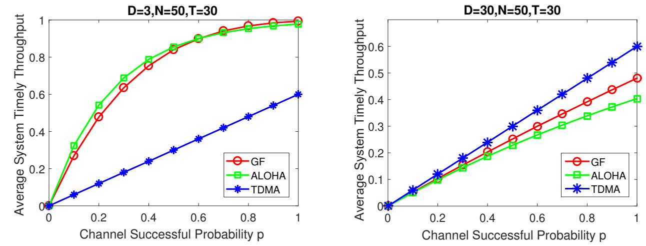
By combining Lemma 1 and Lemma 2, it follows that the lower bound of average system timely throughput of the GF sequence scheme is non-increasing as D increases. Therefore, similar to Sec. IV-A, there exists a D^* such that the GF sequence scheme has better average system timely throughput than TDMA when $D \leq D^*$. On the other hand, we show that when D is large enough, the sequence period of TDMA is less than that of the GF sequence scheme.

[1] A sequence $\boldsymbol{S}$ is blocked by sequences $\boldsymbol{S}_1, \boldsymbol{S}_2, \cdots, \boldsymbol{S}_k$ if there does not exist a slot t such that $S(t) = 1$ while $S_i(t) = 0, \forall i = 1, 2, \cdots, k$.



(a) $T = 30$ (b) $T = 70$

Fig. 1. Compare the empirical value (Emp.) with theoretical value (Theo.) or theoretical lower bound (Theo. LB), and evaluate the effect of topology density D.



(a) $D = 3$ (b) $D = 30$

Fig. 2. Effect of channel quality.

Proposition 1: When $D > \sqrt{2N}$, the sequence period of TDMA is less than that of the GF sequence scheme, i.e., $N < q^2(D, N)$.

Proof: Note that the sequence set in the GF sequence scheme is a ZFD code (see the definition in [35]) and thus the result follows from [35, Theorem 2]. ∎

In our technical report, we give an example to illustrate Proposition 1.

Proposition 1 shows that the average system timely throughput of TDMA is larger than the lower bound of the average system timely throughput of the GF sequence scheme when $D > \sqrt{2N}$. However, it does not mean that the actual average system timely throughput of TDMA is larger than that of the GF sequence scheme when $D > \sqrt{2N}$. We will compare their actual performance by simulations in Sec. V. However in the special case of $D = N - 1$, i.e., all pairs interfere with each other, we can prove that TDMA achieves better system performance than the GF sequence scheme.

Proposition 2: When $D = N - 1$ and N is a prime power, TDMA achieves larger or equal average system timely throughput than the GF sequence scheme.

We remark that although the result in Proposition 2 is heuristically expected, its proof is quite involved.

C. Comparison among TDMA, the GF Sequence Scheme, and the Combination Sequence Scheme for $D = 1$

Due to the page limit, we move the detailed comparison for different schemes when $D = 1$ to our technical report [17].

V. Simulations

In this section, we compare the performance of different topology-transparent distributed schemes by simulations. Due to the page limit, we present key simulations here. Please refer to our technical report [17] for effects of more system parameters, extensions of our model, and simulations for a practical MANET environment.

In terms of average system timely throughput, we compare theoretical value (or theoretical lower bound) and the empirical value. We consider $N = 50$, $T = 30$ or 70 and $p_i = p = 0.8, \forall i \in \{1, 2, \cdots, N\}$. For each topology density $D \in \{1, 3, 5, \cdots, 29\}$, we randomly generate 100 different network topologies and then calculate the mean value of average system timely throughput for all the 100 topologies.

Fig. 1 shows theoretical lower bound and empirical result of ALOHA, theoretical result in (6) and (7) and the empirical result of TDMA, and theoretical lower bound in (9) and (10) and the empirical result of the GF sequence scheme.

From Fig. 1, we can observe that the empirical performance of TDMA matches well with theoretical result, confirming the correctness of (6) (when $N = 50 > T = 30$ as shown in Fig. 1(a)) and (7) (when $N = 50 < T = 70$ as shown in Fig. 1(b)). In addition, we can see that the empirical average system timely throughput of ALOHA is a little bit better than the corresponding theoretical lower bound. The reason is that the number of interferers for any receiver in the average sense is smaller than D, while we derive theoretical lower bound in based on the maximum number of interferers, i.e., D. The empirical average system timely throughput of the GF sequence scheme is much better than the corresponding theoretical lower bound. The reason is that the number of collision-free slots in any period of the GF sequence scheme could be much larger than one as its code weight (number of 1 in a period) is $q > 1$, while we derive theoretical lower bound in (9) and (10) based on the assumption that each sequence has only one collision-free slot in any period.

In addition, we can see that the performance of both ALOHA and the GF sequence scheme degrades when D increases. This is because larger D implies more interferers for a receiver and thus ALOHA is more vulnerable to collision and the GF sequence scheme requires longer sequence period. The performance of TDMA does not change with respect to D, confirming our remark in the last paragraph of Sec. III-A. We further note that the performance of the GF sequence scheme and ALOHA is better than TDMA when D is small. This is because both the GF sequence scheme and ALOHA can exploit the sparsity of the network while TDMA cannot. But when D is large, TDMA dominates others because the performance of ALOHA and the GF sequence scheme degrades when D increases while that of TDMA does not change. This confirms our analysis in Sec. IV-A and Sec. IV-B.

We also evaluate the effect of channel quality p_i. We assume that all pairs have the same channel quality, i.e., $p_i = p, \forall i \in \{1, 2, \cdots, N\}$, where p varies from 0 to 1. We set $N = 50$, $T = 30$, and $D = 3$ or 30. For each D, we randomly generate 100 topologies. For each p, we run 100 times for each of the 100 topologies, and then calculate the mean value of average system timely throughput. The throughput performance of ALOHA, TDMA and the GF sequence scheme is shown in Fig. 2. We can see that in all schemes, better channel quality leads to larger average system timely throughput. This is an obvious result. Again, similar to the analysis for Fig. 1, the performance of the GF sequence scheme and ALOHA is better than TDMA when D is small ($D = 3$), while TDMA has the best performance when D is large ($D = 30$).

In addition, when D is small and channel quality p is small, ALOHA is better than the GF sequence scheme. We have also carried out many other instances to confirm this observation. This shows that although both ALOHA and the GF sequence scheme improve their performance when D decreases, the improvement of ALOHA outperforms that of the GF sequence scheme when the channel quality is low.

VI. Conclusion

In this paper, distributed scheduling designs for a topology-transparent MANET to support delay-constrained traffic are

TABLE I
SUMMARY OF THE BEST SETTINGS FOR DIFFERENT SCHEMES.

Schemes	Best Settings
ALOHA	Network density D is small and channel quality $\{p_i\}$ is small
TDMA	Network density D is large
The GF Sequence Scheme	Network density D is small and channel quality $\{p_i\}$ is large
The Combination Sequence Scheme	Network density $D = 1$

investigated for the first time. We have analyzed and compared the average system timely throughput of several schemes including ALOHA, TDMA, the GF sequence scheme and the combination sequence scheme. Different schemes work best for different settings. We have summarized their individual best settings in Table I according to our analysis and simulations in this paper.

Our main contribution in this work is that we have analyzed and compared different distributed schemes which were generally designed for delay-unconstrained setting. In the future, it would be interesting to design a novel distributed scheme that is particularly suitable for delay-constrained setting. Here we give some of our thoughts on how to design such a new scheme. One direction is to design a *hybrid* scheme combining both the deterministic sequence scheme and the probabilistic scheme. The sequence scheme utilizes the network topology elegantly such that each user has at least one collision-free slot in a period. However, once two or more pairs have bit '1' in the same slot, they will collide for sure. The probabilistic scheme can soften the collision such that a user can still have chance to deliver its packet successfully even other users also have bit '1' in the same slot. It is possible to combine the benefits of both the deterministic sequence scheme and the probabilistic scheme to design a better hybrid scheme. Another direction is to re-design the sequence assignment mechanism. In our paper, we assume that sequences are pre-assigned to the users and a user will keep using its assigned sequence all the time. This approach looks inflexible. It is possible to design a sequence pool from which each user can randomly select a sequence [36]. Users can also adaptively change the sequences. This approach increases the flexibility. The research problem is how to design a good sequence pool. We will work along these directions in the future.

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