A Novel Multiple Access Scheme with FPP Intermixed Grouping for Wireless Sensor Networks

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Abstract **—Energy efficient multiple access design is crucial for wireless sensor networks. In this letter, we propose a novel scheme with intermixed grouping to enhance energy efficiency and throughputs based on the theory of finite projective plane. We map the set of points of finite projective plane into the time slots of transmission of a node and vary the transmit probabilities among transmitting nodes. Fairness is guaranteed for each node and slot with the sum probability equal to one and cycle in a round-robin style. Since the grouping is intermixed, a node with heavy data load will not hurt the chance of transmission of other nodes consistently. While traffic is light or heavy, the transmit probability is scaled up or down among all nodes to optimize the chance of successful transmission to avoid excessive collisions. Energy saving and throughput are achieved through the scalable transmit probabilities.**

I. INTRODUCTION

Wireless sensors networks (WSNs) are developed for many event-triggered applications such as automation, monitoring and surveillance, and so on. In general, sensor nodes have stringent resource constraints such as energy and processing capability. The limited resource and capability make the data generated by sensor nodes unreliable and inaccurate [1-2]. When battery power is nearly exhausted, the probability of generating erroneous data will often occur [3-4]. There are two main categories of multiple access in a shared wireless medium: (1) contention based and (2) reservation based [2]. In reservation based approach, the network structure needs to be planned ahead of time and each node has to follow a schedule in order to communicate with each other. In contention based approach, the idea is rather straightforward. The node with a "good luck" in competition is allowed to access the wireless medium. However, the contention based approach suffers a disadvantage. When the network load increases, the throughput drops significantly. Moreover, the design criteria for conventional multiple access are not applicable to WSNs [5]. Reviews of multiple access schemes for WSNs have been provided in [6]. Many multiple access protocols are intended to achieve energy saving through either reduction of collisions, avoidance of overhead, reduction on overhearing, or elimination of idle listening, which are main causes of energy consumption in WSNs [7].

In this paper, we propose a novel multiple access scheme with variable transmit probabilities (VTP) and intermixed grouping of nodes based on the theory of finite projective plane (FPP) [8]. For the past several years, many researches for FPP characteristics and applications based on FPP theory have been explored continuously by Woo and other researchers, e.g., orthogonal variable spreading codes for wideband CDMA, channel assignment with limited channel-sharing in cellular networks, optimal time-hopping scheme for CDMA air interface in broad-band wireless systems, and etc [9-14]. There are two important properties in finite projective planes. i.e., each pair of sets intersects at exactly one point and the number of occurrences of a point number among the sets is constant. We map the set of points of FPP into the time slots of transmission of a node and vary their transmit probabilities with Latin square of sum equal to one for each node. Since the sum of variable transmit probability is one, fairness is guaranteed while a node is competing with other nodes. A node with heavy data load will not hurt the chance of transmission of other nodes consistently due to intermixed grouping. When the network load is heavy, it is scaled down to avoid excessive collisions. Energy saving and throughput are achieved through the scalable transmit probabilities.

The remainder of this paper is organized as follows. In Section II, a finite projective plane basic is addressed. The arrangements of nodes and slots available for the multiple access schemes without grouping and with fixed grouping are addressed in Section III and IV, respectively. In Section V, the proposed intermixed grouping combined with the benefits of fixed grouping and VTP is addressed. In Section VI, intriguing numerical results based on the proposed metrics are illustrated. Conclusion is in final Section VII.

II. FINITE PROJECTIVE PLANE BASICS

A finite projective plane (FPP) is basically a geometry that satisfies the condition that any two lines intersect in exactly one point. For example, the finite projective plane called Fano plane with order m=2 is shown in **Fig. 1**. We see that the difference between affine (e.g., Euclidean plane) and projective planes is that parallel lines exist for the former ones, whereas in projective planes lines always meet.

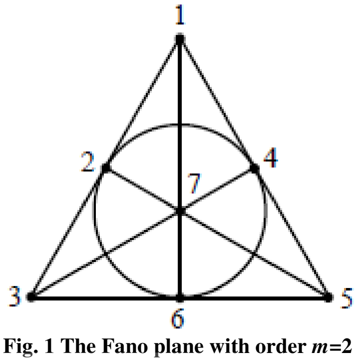

Fig. 1 The Fano plane with order m=2

In short, based on the basic FPP theory, a FPP of N points has the following properties:

1) A finite projective plane of *N points* consists of *N sets of points*.
2) Each set has exactly m+1 points, where $m^2+m+1=N$. The value of m is also called the order of the finite projective

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plane, e.g., N=7 if m=2.

3) Two distinctive sets intersect at exactly one point. For example, a FPP of 3 points (m=1) has sets $A1$= (1, 2), $A2$= (1, 3), and $A3$= (2, 3). A FPP of 7 points (m=2) called Fano plane has (line) sets of A_1= (1, 2, 3), A_2= (1, 4, 5), A_3= (1, 6, 7), A_4= (2, 4, 6), A_5= (2, 5, 7), A_6= (3, 5, 6), and A_7= (3, 4, 7). Similarly, the sets for a FPP of 13 points (m=3) are as follows: (1,2,3,4), (1,5,6,7), (1,8,9,10), (1,11,12,13), (2,5,8,11), (2,6,9,12), (2,7,10,13), (3,5,10,12), (3,6,8,13), (3,7,9,11), (4,5,9,13), (4,6,10,11), and (4,7,8,12) [6].

Therefore, there are at least two important properties in finite projective planes. First, each pair of sets intersects at exactly one point. Second, the number of occurrences of a point number among the sets is constant. To be precise, each point appears in 3 out of the total 7 sets if the FPP order m is two and they are intermixed each other. There are two creative and distinguishing features for the proposed approach to enhance energy efficiency and throughput. First, a scalable and variable transmit probability (VTP) is initiated, while a node transmits with a high probability when the traffic load is low, and transmits with a low probability when the traffic load is high. Second, intermixed grouping based on the FPP theory is proposed. With intermixed grouping, a node competes with different groups of nodes with fairness guaranteed (sum=1). A node with heavy data load will not consistently affect the chance of transmission of other nodes. **Table 1** shows this typical FPP resources allocation scheme (m=2) with VTP (β= 1/6) combined with Latin square of dimension of three.

Table 1 A FPP scheme (m=2) with VTP (β= 1/6), intermixed grouping, and fairness

S / N	1	2	3	4	5	6	7
1	$\frac{1}{6}$	$\frac{2}{6}$	$\frac{3}{6}$				
2	$\frac{2}{6}$			$\frac{3}{6}$	$\frac{1}{6}$		
3	$\frac{3}{6}$					$\frac{2}{6}$	$\frac{1}{6}$
4		$\frac{3}{6}$		$\frac{2}{6}$		$\frac{1}{6}$	
5		$\frac{1}{6}$			$\frac{3}{6}$		$\frac{2}{6}$
6			$\frac{1}{6}$		$\frac{2}{6}$	$\frac{3}{6}$	
7			$\frac{2}{6}$	$\frac{1}{6}$			$\frac{3}{6}$

III. MULTIPLE ACCESS WITHOUT GROUPING

The arrangement of nodes and slots available for the conventional multiple access scheme without grouping is a rather generic scheme for selecting time slots for nodes to transmit as shown in **Table 2**, where the node (N) and the slot number (S) are both set as seven (7). The fixed transmit probability 1/7 is set to each slot, therefore, the transmit variability β= 0. For instance, a time frame of 7 time slots is shared by 7 nodes (numbered 1 through 7).

Table 2 Fixed transmit probability scheme without grouping (β= 0)

S / N	1	2	3	4	5	6	7
1~ 7	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{7}$

The throughput defined for this scheme with fixed transmit probability without grouping (β= 0) is therefore given as

$$T_{ng}^{0}=\sum_{i=1}^{N}\left(\frac{1}{N}\cdot\prod_{j=1,j\neq i}^{N}\left(1-\frac{1}{N}\right)\right) \qquad (1)$$

where N is set to equal to both the node number and the time slot number for fair comparison with other schemes without loss of generality. Without loss of generality, it is defined as the sum of successful transmission while all other nodes withhold.

The other multiple access scheme without grouping, but with transmit variability ($\beta\neq 0$), is shown in **Table 3**, where the node and the slot number are both set as seven (7) with variable transmit probability and transmit variability β= 1/28. For instance, a time frame of 7 time slots is shared by 7 user nodes (numbered 1 through 7) with variable transmit probability from 1/28 to 7/28. The transmit probability of a cell is calculated by the number of a cell divided by the sum of a Latin square of dimension 7, i.e., 28. Note that the sum of transmit probabilities of either a row or a column is equal to one and cycle in a round-robin style for fairness. It can be also scaled down if the network load is heavy and scaled up if the network load is light.

Table 3 VTP scheme without grouping (β= 1/28)

S / N	1	2	3	4	5	6	7
1	$\frac{1}{28}$	$\frac{2}{28}$	$\frac{3}{28}$	$\frac{4}{28}$	$\frac{5}{28}$	$\frac{6}{28}$	$\frac{7}{28}$
2	$\frac{7}{28}$	$\frac{1}{28}$	$\frac{2}{28}$	$\frac{3}{28}$	$\frac{4}{28}$	$\frac{5}{28}$	$\frac{6}{28}$
…	Round-robin						
7	$\frac{2}{28}$	$\frac{3}{28}$	$\frac{4}{28}$	$\frac{5}{28}$	$\frac{6}{28}$	$\frac{7}{28}$	$\frac{1}{28}$

The throughput defined for this scheme with fixed transmit probability without grouping (β=1/N) is therefore given as

$$T_{ng}^{N}=\sum_{i=1}^{N}\left(\frac{2i}{N^2+N}\cdot\prod_{j=1,j\neq i}^{N}\left(1-\frac{2j}{N^2+N}\right)\right) \qquad (2)$$

IV. MULTIPLE ACCESS WITH FIXED GROUPING

For fixed grouping, we first divide the N nodes into different groups and then apply the VTP scheme to each of the groups, e.g., $N^{1/2}$, $N^{1/3}$, and etc. Based on a Latin square of dimension 3, the transmit probability assignment with $N^{1/2}$=3 groups (N=9) can be arranged for illustration. The transmit probability of a grouped cell in the matrix is determined by the number in a cell divided by the sum of a Latin square of dimension 3, i.e., 6. A group of three nodes has variable transmit probabilities assigned as 1/6, 2/6, and 3/6, respectively. Thus the sum of transmit probabilities of either a row or a column is equal to one. It can be also scaled up or down dependent on the network loads.

We now describe how the variable transmit probability scheme can be used for fixed grouping. Once again, we use nine nodes as an example. Without loss of generality, we divide the nodes into three groups, each of which has three nodes. The nodes in a group transmit according a Latin square of dimension 3. The transmit probability of a cell is calculated by the number of a cell divided by the sum of a Latin square of dimension 3. As noted in **Table 4**, with a simple fixed group, the variability of the transmit probability is increased. The transmit probability assignment can have the benefits of both variable transmit probability and fixed grouping, but not the inter-mixed grouping.

Table 4 Variable transmit probability scheme with fixed grouping (nine nodes)

S / *N*	1	2	3	4	5	6	7	8	9
1	$\frac{1}{6}$	$\frac{2}{6}$	$\frac{3}{6}$						
2	$\frac{3}{6}$	$\frac{1}{6}$	$\frac{2}{6}$						
3	$\frac{2}{6}$	$\frac{3}{6}$	$\frac{1}{6}$						
4				$\frac{1}{6}$	$\frac{2}{6}$	$\frac{3}{6}$			
5				$\frac{3}{6}$	$\frac{1}{6}$	$\frac{2}{6}$			
6				$\frac{2}{6}$	$\frac{3}{6}$	$\frac{1}{6}$			
7							$\frac{1}{6}$	$\frac{2}{6}$	$\frac{3}{6}$
8							$\frac{3}{6}$	$\frac{1}{6}$	$\frac{2}{6}$
9							$\frac{2}{6}$	$\frac{3}{6}$	$\frac{1}{6}$

V. PROPOSED MULTIPLE ACCESS WITH INTERMIXED GROUPING BASED ON FPP

With a simple fixed grouping, the variability of the transmit probability is increased obviously. There are two advantages, i.e., reducing the amount of interference of time slots in case that a user node is in a malfunctioned state, and varying the "victims" of collision due to an aggressive node. The idea is to let all other nodes to equally share the burden of an aggressive node. Thus, no node will suffer disastrous damage. Furthermore, the intermixed grouping can combine with the VTP to enjoy these benefits. As shown in **Table 5**, we select the FPP cases of seven-point for illustration purpose ($m^2+m+1=N$, $m+1=3$). There are seven competing nodes for each case, respectively. For each case there are three intermixing time slots. The transmit probabilities are assigned based on the points of a set of FPP of seven points, and the sum of transmit probability of a column or a row is equal to one. A group of three nodes has VTP assigned as 1/6, 2/6, and 3/6, respectively.

Table 5 VTP scheme with intermixed grouping (β= 1/3)

S / *N*	1	2	3	4	5	6	7
1	$\frac{1}{6}$	$\frac{2}{6}$	$\frac{3}{6}$				
2	$\frac{2}{6}$			$\frac{3}{6}$	$\frac{1}{6}$		
3	$\frac{3}{6}$					$\frac{2}{6}$	$\frac{1}{6}$
4		$\frac{3}{6}$		$\frac{2}{6}$		$\frac{1}{6}$	
5		$\frac{1}{6}$			$\frac{3}{6}$		$\frac{2}{6}$
6			$\frac{1}{6}$		$\frac{2}{6}$	$\frac{3}{6}$	
7			$\frac{2}{6}$	$\frac{1}{6}$			$\frac{3}{6}$

The throughput defined for this scheme with both VTP and intermixed grouping (β= 1/m) is given as

$$T_{mg}^{m}=\sum_{i=1}^{m}\left(\frac{2i}{m^2+m}\cdot\prod_{j=1,\,j\neq i}^{m}\left(1-\frac{2j}{m^2+m}\right)\right) \qquad (3)$$

where m is set equal to both node number and time slot number for fair comparison with other schemes; m must be also set equal to the solution of $m^2+m+1 = N$, i.e., $m =(-1+(4N-3)^{1/2})/2$.

VI. PERFORMANCE EVALUATION

The proposed scheme can improve both throughput and energy efficiency gain. The energy efficiency gain (η) is defined to be the gain available when compared to the β=0 multiple access case without grouping, i.e., equation (1). **Fig. 2** and **Fig. 3** illustrate the throughput and energy efficiency gain available for different transmit variability, i.e., β=0, 1/N, and 1/(m+1), respectively. The proposed scheme with both VTP and intermixed grouping shows significant improvements in comparison with the other two homogeneous transmit probability schemes without grouping, i.e., β=0 and β=1/N, especially when the number of nodes is small. As the number of nodes increases, the improvement decreases due to a reduced variability of transmission probabilities among nodes. The VTP is useful especially when the variability in transmit probabilities among user nodes are high. In other words, the greater the variability, the higher the performance gain of the variable transmit probability scheme.

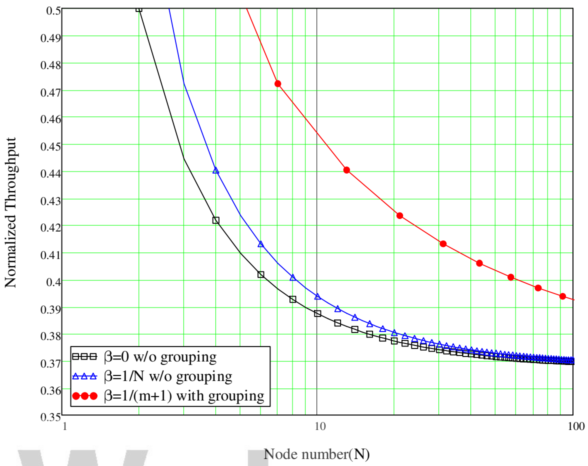

Fig. 2 Throughput comparison for different transmit variability, i.e., β=0, 1/N, and 1/(m+1)

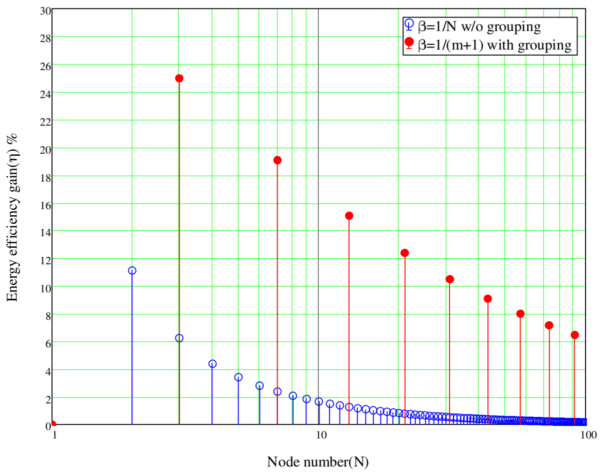

Fig. 3 Energy efficiency gain (η) for different transmit variability (relative to β= 0), i.e., energy efficient gains available for β= 1/N and 1/(m+1)

VII. CONCLUSION

We have proposed an intermixed grouping scheme based on the theory of FPP with VTP for WSNs applications. Energy saving and throughput are achieved through the scalable transmit probabilities. There are many advantages using the proposed grouping scheme. First, both energy efficiency and throughput are improved. Secondly, a node with heavy data load only affects other nodes in some time slots, and thus giving the rest of nodes a breathing room due to intermixed grouping. Thirdly, fairness is guaranteed by summing the probability equal to one for each node and slot. Furthermore, the proposed scheme come with little price to pay.

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