A Switch Model for Improving Throughput and Power Fairness in Bluetooth Piconets

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***Abstract*— In this paper, a model for N mobile nodes that talk to one another simultaneously is considered under the following constraint: No node may transmit and receive at the same time. Furthermore, we focus on a Personal Area Network (PAN) application limiting the network to a single-hop ad-hoc network. The resulting half-duplex wireless network is an interesting special case of the general full-duplex multi-hop ad-hoc networks. We model the system of the wireless channel and the N nodes as an $N \times N$ switch. We call a PAN based on this model a Switched PAN (S-PAN). The model is motivated by some limitations of the current specification of Bluetooth and by recent amendments of the rules governing the free-license ISM bands by the Federal Communications Commission. A specific Bluetooth-based S-PAN network that requires minimal changes to the current Bluetooth specification is introduced. The Bluetooth-based S-PAN is shown to outperform the current Bluetooth specification in throughput, delay, and energy-fairness to masters. Specifically, the S-PAN piconet is shown to achieve a throughput of up to 5 times (and possibly higher) the throughput of an equivalent Bluetooth piconet.**

I. Introduction and Motivations

There are many proposals in the literature for multiaccess protocols that allow N mobile nodes to communicate with one another as an autonomous system [6]. We consider *statistical multiplexing* mechanisms that provide quality-of-service (QoS) guarantees in a wireless PAN environment. We use the Bluetooth [3] as an example of a PAN network and we demonstrate the advantages of the proposed scheme by comparing it to the current specification of Bluetooth.

This paper addresses and improves limitations in the current specification of Bluetooth.[1] Specifically, although the role of the master is crucial in controlling the access to the channel and hence providing time-sensitive services, we believe that it is unfair for the master to relay all the traffic of the piconet. In a PAN such as Bluetooth where each node is assumed to be in the range of every other node (at least within a piconet), it is unnecessary and inefficient to let the master forward all traffic of the piconet. It will be ideal if the nodes in a piconet can talk *simultaneously and directly* to one another *without collisions*. In this paper, we first propose a general model and framework to achieve this, then we design a specific instance of the general framework based on the current Bluetooth specification.

[1]We refer the reader to [4], [5] or the core specification [3] for a background or a comprehensive overview of Bluetooth, respectively.

This paper is organized as follows. Section II discusses a general model and framework of PANs and our assumptions. In section III, we propose and analyze a specific PAN that requires minor modifications to the current Bluetooth specification and outperforms it. Concluding remarks and future work are discussed in section IV.

II. System Model and Assumptions

We model an autonomous system of N mobile nodes and the wireless channel as an $N \times N$ switch. Each mobile node is assumed to have a single transmitter and a single receiver. In practice and for economical reasons, the single transmitter and single receiver on a mobile node are usually combined in a single "transceiver" which alternates between a transmitter and a receiver. In this case, the node can not transmit and receive at the same time. We term this the Half-duplex (Hd) constraint.

In the above mentioned model, a centralized scheduler collects, via a control channel, global network information. The scheduler uses a slotted system and a *matching algorithm*[2] to match transmitters to their intended receivers. Clearly, there is no need for a transmitter to transmit to the receiver on the same mobile node. Therefore, the possibility of a transmitter sending to the receiver on the same mobile node is disallowed. The resulting system of N transmitters and N receivers, with exactly one transceiver on each mobile node, can be modelled as a special case of an $N \times N$ switch [1]. The N transmitters can be thought of as the N input ports of a switch and the N receivers as the N output ports. The centralized scheduler node is modelled as the arbiter or scheduler of the switch. This PAN model assumes that each node's transmission can reach any of the other $N-1$ nodes and the central node[3]. It is also assumed that enough distinct channels (frequencies) are available in each scheduling opportunity and that each transmitter and each receiver can tune in to any of these frequencies. Alternatively, a Code Division Multiple Access (CDMA) system may be used.

[2]A *matching* in a *bipartite graph* $G = (V \cup U, E)$ is a subset of edges in G (i.e., of E) such that no node in V or in U has more than one edge of this subset incident on it. A *maximal* matching in a bipartite graph is any matching such that given this matching, no other edge can be added to it without violating the definition of the matching. A *maximum* matching in a bipartite graph G is a matching consisting of the maximum possible number of edges in G.

[3]Note that the central node or the scheduler could be either one of the N nodes or a separate entity.

We call a PAN based on this model a Wireless Switched PAN or simply a Switched PAN (S-PAN). With these assumptions, the model can be represented by a special *bipartite graph* as depicted in figure 1. For future reference, let us define this special case of bipartite graphs as the *N-Node Bipartite Graph* (NNBG).

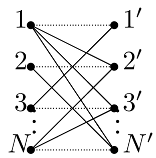

Fig. 1. A model in which the N mobile nodes and the wireless channel are modelled as an $N \times N$ switch. A dotted horizontal line indicates that a node i, on the left representing a transmitter, and the corresponding node i', on the right representing a receiver, are on the same physical mobile node. We call this special bipartite graph the N-Node Bipartite Graph (NNBG).

The "maximal" matchings in an NNBG that satisfy the Hd constraint will be used to provide QoS guarantees in half-duplex ad-hoc networks. We call these "maximal" matchings, the *Half-duplex Constrained Maximal (HdCM) matchings*.

III. A Bluetooth-based S-PAN

In this section, we consider Bluetooth as a specific example of PAN networks against which we compare the performance of our approach. We will show, in this section, the gains in throughput, and fairness in power consumption to masters. In order to do that, we will propose a scheduling scheme, based on our switch model, that requires minor modifications to the current Bluetooth specification. Specifically, we will demonstrate how to utilize the approach developed in section II and minor changes to the current Bluetooth specification to design a new piconet that is far more efficient and fair (to the masters) than an equivalent current Bluetooth piconet. For convenience, in the remaining of this paper we will refer to this "Bluetooth-based instance of the S-PAN" simply as the S-PAN.

A. The basic algorithm

Consider an established Bluetooth piconet with K slaves, and $N = K + 1$ nodes including the master. According to the Bluetooth specification, the communication channel is defined as a pseudo-random hopping-sequence determined by the Master's ID and clock. Assume that each node in the piconet (active or non-active) is uniquely identified by a 1-byte address[4], where we assume that the all-zeros 8-bit address identifies the master.

During each Bluetooth time-slot, each two communicating nodes are *matched* directly to each other using a distinct hop-frequency. Later, in section III-E, we will provide a specific algorithm to assign hop-frequencies to all communicating pairs in the piconet without collision.

In order to match communicating nodes without collision, three *basic steps* take place in the following order. First, the slaves communicate to the master their "requests", which could be for example, the destination nodes of their transmissions and the size of their queues for each of those destinations. Second, the master computes a *conflict-free* matching between requesting transmitters and their intended receivers. Third, the master conveys the computed schedule to all slaves (not only the requesting slaves). In the following subsections we elaborate and define the specifics of these basic steps.

The basic S-PAN algorithm repeats every F time-slots, where F, the frame-length, is *variable*. First, the master polls the slaves. Assume that P time-slots is used for polling. Second, the slaves respond. Assume that R time-slots is used for the response of all slaves. Third, the master broadcasts a schedule. Assume that B time-slots is used for the schedule broadcast. Let $A = P + B$. Lastly, the nodes are interconnected. Assume that I time-slots is used for the interconnection, where we assume that the maximum number of time-slots scheduled by the master in any frame is T^{sch}_{max}. Therefore, $F = P + R + B + I$. Figure 2 shows the basic components of the S-PAN frame.

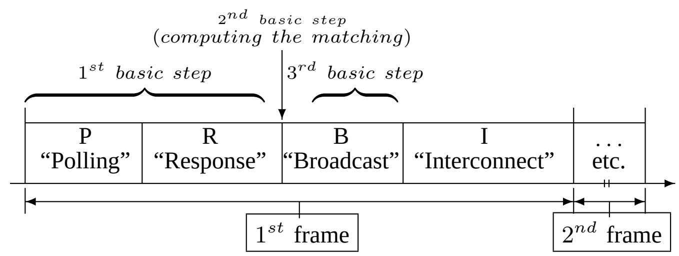

Fig. 2. The basic structure of the S-PAN's scheduling (variable-length) frame. The length of the frame measured in time-slots is F, where by design $F = P + R + B + I$. We assume this structure when $2 \leq K \leq N - 1$, and the case $K = 1$ is treated separately.

An important Exception: The $K = 1$ Case: When only one active slave exists in the piconet, an important and common case in practice, there is no need for "polling", "response", and then "broadcasting" a schedule. The most efficient way in this case is the Bluetooth technique, the channel is equally time-divided between the master and *the* slave in an alternating fashion. Therefore, the S-PAN piconet reduces (by design) to a Bluetooth piconet whenever only one active slave exists in the S-PAN piconet.

B. Polling slaves and submitting requests by slaves

The polling-packet: To avoid collisions, slaves may submit their requests only after the master broadcasts a "polling" packet to poll slaves to submit their requests in a predefined form. Since some slaves could be "parked" and since a slave may not be aware of all other slaves in the piconet, the polling packet contains a *list* of identifiers for the current active members of the piconet. As discussed earlier, to accommodate $N = 256$ in a piconet, a 1-byte identifiers are used. Hence, the polling packet is simply a *list* of 1-byte identifiers.

[4]We chose a 1-byte identifier to extend the maximum allowable number of active slaves in a piconet beyond 7. If the application of the piconet does not require the number of active slaves to exceed 7, the 3-bit Active Member Address of Bluetooth, `AM_ADDR`, may be used instead. Note that applications requiring large number of active slaves exist but not discussed in this paper.

Submitting requests: Only the slaves listed in the polling packet *must* respond in the following Bluetooth time-slots in the same order in which their identifiers were listed in the polling packet by the master. All other slaves not listed in the polling packet may not respond. Note that the number of slots required for the slaves to sequentially submit their requests is R, where $K \leq R \leq \alpha K$, and α is chosen such that $\alpha \leq 3$.

C. Computing the schedule by the master

Once the master has all requests from all active slaves, then considering its own requests, the master computes *any* maximal matching that satisfies the half-duplex constraint. The reason for computing *any* maximal matching is the ease of computing such a matching. However, computing a maximum matching instead is also permitted in the analysis of section III-F.

D. Broadcasting the schedule by the master

The schedule is essentially a *set* of computed *matchings*. Each matching is to be executed over a distinct Bluetooth time-slot. Each communicating pair in a matching tunes in to a hop-frequency determined by the hopping algorithm described later in section III-E. Assume that a maximum of $N = 256$ nodes may need to be matched. In this case, a *list* of the 8-bit member-addresses will suffice to convey the schedule to the members (assuming the all zeros 8-bit address identifies the master). Therefore, a 16-bit field is sufficient to describe the two nodes matched to each other, where by definition, the first 8-bit indicates the transmitter and the second 8-bit indicates the intended receiver.

E. An algorithm for determining the next frequency-hop

A new kernel or the same kernel specified in the current Bluetooth specification to generate the hopping-sequence may be used in conjunction with the following algorithm. Assume that the master broadcasts a polling packet at time-slot 0 on some frequency, $f(0)$, of the hopping-sequence. Since the polling packet has an *ordered list* of K active members, let each member i of this list has the i^{th} hop, $f(i)$, among the following K hops of the sequence, dedicated to its response during the i^{th} time-slot of the next K time-slots. Therefore, the $(K+1)^{th}$ hop in the sequence, $f(K+1)$, is the hop where all members should tune in to receive the broadcast schedule from the master during the $(K+1)^{th}$ time-slot. Once they received the schedule, the hop to be used by each pair as well as who transmits and who receives of each pair are *encoded* in the format of the schedule. This is done by listing the schedule (as described in section III-D) in the form of transmitter-identifier/receiver-identifier pairs.

F. Analysis of the S-PAN and comparison to Bluetooth

We will consider some performance limits of the S-PAN and compare these limits to an equivalent setting of Bluetooth.

In this paper, we focus on the performance of a single piconet. We will denote our scheme as the "S-PAN" and compare it when possible to a Bluetooth piconet, denoted by "BT" (for Bluetooth). For the comparison to Bluetooth to be meaningful, we restrict N to be $2 \leq N \leq 8$, in accordance with the current specification. However, for the S-PAN, N may generally take on higher integer values (not higher than 256, however). Note also that we are using the term "time-slot" interchangeably with the term "Bluetooth time-slot". Assume that the maximum allowed number of channels (or frequency hops) that can be used concurrently by the S-PAN in a single time-slot is M^{ch}_{max}.

We need the following definitions to measure the "throughput" performance of a S-PAN piconet and compare it to a Bluetooth piconet, under similar settings. The *increase in "throughput"* is most needed when the piconets are handling heavy loads. Fortunately, the "increase in throughput" is well defined to compute in this case. We define these quantities more precisely next.

Definition 1: (Heavy load condition) We define *heavy load* condition to mean that every node in the piconet always has data to send to every other node in the piconet.

Definition 2: (Throughput-packets, overhead-packets) By *throughput packets* we mean all user *data packets* counted only once when received by the destination. By *overhead packets* we mean all transmitted packets *except* the throughput packets. For example, when the master relays a packet from one slave to another slave, we define the packet transmitted from the source to the master as "overhead-packet" and the packet transmitted (relayed) by the master and received by the second slave as a "throughput-packet". In the S-PAN, all polling, slave-requests, and schedule-broadcast packets are defined as overhead packets.

During a given interval T, the parallelism in the S-PAN piconet allows for transmitting "total packets" greater than T, while in a Bluetooth piconet, the maximum number of total transmitted packets during T is T. In order to compare the throughput of a S-PAN piconet to that of an equivalent (in size and traffic pattern) Bluetooth piconet, we define next the "throughput-increase factor", which essentially compares the total throughput-packets transmitted in an interval T.

Definition 3: (Throughput-increase factor) Let the throughput packets of a Bluetooth piconet of N nodes over T time-slots be $Th^{BT}(T)$ and the throughput packets of a S-PAN piconet of N nodes fed the same traffic pattern over the same interval, T, be $Th^{S\text{–}PAN}(T)$. We define the *throughput-increase factor* during the interval T, $\gamma(T)$, as the ratio of the throughput packets of the S-PAN to the throughput packets of the Bluetooth, i.e.,

$$\gamma(T) = \frac{Th^{S-PAN}(T)}{Th^{BT}(T)}. \tag{1}$$

And $\gamma = \lim_{T\to\infty} \gamma(T)$ if it exist.

Definition 4: (Notational convention) Under the heavy load condition of definition 1, we denote the quantity γ by γ_∞. We will use this convention as appropriate with other quantities as well.

For a fair comparison of throughputs, it is critical to note that under the heavy load condition, we need to assume that the

BT master will not "starve" any active slave from sending to any other slave for a long period. This could happen if the BT master, having infinite load, only serves packets originating from the master to slaves and destined to the master from slaves. The comparison to a S-PAN piconet will not be fair without this assumption since the S-PAN piconet does not have such a peculiar situation. Thus for a fair comparison of throughputs, we need the assumption formalized in the next definition.

Definition 5: (Slave-to-slave (STS) assumption) We assume that no active slave is starved from sending to any other slave for a period more than it normally would in a round robin scheme that allows each node to send to every other node in the network. More precisely, under the heavy load condition of definition 1, no slave in a piconet of K active slaves is starved from sending to any other member (a slave or the master) in the piconet for more than $2K^2 + Z$ consecutive time-slots[5], where Z is a constant.

Due to space limitation, we will state the following results without proofs. The proofs may be found in [1].

CLAIM 1: (Asymptotic throughput comparison) With the STS assumption of definition 5, the asymptotic *throughput-increase factor* is such that: Under the heavy load condition of definition 1:

$$\alpha_1 \leq \gamma_\infty \leq \alpha_2, \quad \text{where} \tag{2}$$

$$\alpha_1 = \frac{2K^2\alpha^* T^{sch}_{max}}{(K^2+K)(A+\alpha K+T^{sch}_{max})},$$

$$\alpha_2 = \frac{2K^2\alpha^* T^{sch}_{max}}{(K^2+K)(2+K+T^{sch}_{max})},$$

and $\alpha^* = \min\{M^{ch}_{max}, \lfloor \frac{K+1}{2} \rfloor\}$.

The *energy fairness* to masters who have to do extra work so that the network functions properly is an important consideration in this study. Every packet transmitted (or received) by the master that is not part of the master's *data* or payload may be considered an unfair expenditure of the master's energy resources. In the next claim, we compare the *energy overhead* of the S-PAN piconet to that of an equivalent Bluetooth piconet. As a corollary of this claim, we will be able to compare the *energy fairness of the master* of a S-PAN piconet to that of the master of an equivalent Bluetooth piconet.

In order to perform a comparison, we need the following assumptions and definitions.

Definition 6: (Energy-saving factors of the S-PAN piconet and of the master of the S-PAN) Assume that all transmitted packets are of equal length of one unit. Define every overhead packet transmitted in the piconet to correspond to $e_t + e_r$ units of unfairly expended energy, where e_t units are expended by the transmitter and e_r units are expended by the receiver. Let e_t correspond to one normalized unit of energy and define $\mu = e_r/e_t$.

[5] It can be shown that $2K^2$ is the minimum number of time-slots required for each node of the Bluetooth piconet to send at least one packet to every other node [1].

1) Let the *overhead packets* of definition 2 during an interval T for a Bluetooth piconet and a S-PAN piconet be denoted as $OP^{BT}(T)$ and $OP^{S\text{–}PAN}(T)$, respectively. Define the *piconet energy-saving factor* during an interval T, and under heavy load condition, $\varepsilon^{piconet}_\infty(T)$, as

$$\varepsilon^{piconet}_\infty(T) = \frac{OP^{BT}(T)/T}{OP^{S\text{–}PAN}(T)/T}. \tag{3}$$

And $\varepsilon^{piconet}_\infty = \lim_{T\to\infty} \varepsilon^{piconet}_\infty(T)$ if it exist.

2) Let the *overhead packets* of definition 2 that are *transmitted by the master* during an interval T for a Bluetooth piconet and a S-PAN piconet be denoted as $OP^{BT}_{master,t}(T)$ and $OP^{S\text{–}PAN}_{master,t}(T)$, respectively. Let the *overhead packets* of definition 2 that are *received by the master* during an interval T for a Bluetooth piconet and a S-PAN piconet be denoted as $OP^{BT}_{master,r}(T)$ and $OP^{S\text{–}PAN}_{master,r}(T)$, respectively. Define the *master energy-saving factor* during an interval T, and under heavy load condition, $\varepsilon^{master}_\infty(T)$, as

$$\varepsilon^{master}_\infty(T) = \frac{[OP^{BT}_{master,t}(T) + \mu OP^{BT}_{master,r}(T)]/T}{[OP^{S\text{–}PAN}_{master,t}(T) + \mu OP^{S\text{–}PAN}_{master,r}(T)]/T}. \tag{4}$$

And $\varepsilon^{master}_\infty = \lim_{T\to\infty} \varepsilon^{master}_\infty(T)$ if it exist.

CLAIM 2: (Asymptotic comparison of energy overhead in the piconets) Under heavy load condition and the assumptions of definition 6, the *piconet energy-saving factor*, $\varepsilon^{piconet}_\infty$, is such that

$$e_1 \leq \varepsilon^{piconet}_\infty \leq e_2, \quad \text{where} \tag{5}$$

$$e_1 = \frac{(K^2-K)(A+\alpha K+T^{sch}_{max})}{2K^2(A+\alpha K)},$$

$$e_2 = \frac{(K^2-K)(2+K+T^{sch}_{max})}{2K^2(2+K)}.$$

Corollary 1: (of claim 2) (Asymptotic comparison of energy overhead of masters of the piconets) Under heavy load condition and the assumptions of definition 6, the *master energy-saving factor*, $\varepsilon^{master}_\infty$, is such that

$$e_3 \leq \varepsilon^{master}_\infty \leq e_4, \quad \text{where} \tag{6}$$

$$e_3 = \frac{(1+\mu)(K^2-K)(A+\alpha K+T^{sch}_{max})}{2K^2(A+\mu\alpha K)},$$

$$e_4 = \frac{(1+\mu)(K^2-K)(2+K+T^{sch}_{max})}{2K^2(2+\mu K)}.$$

G. Discussion of the results

We discuss the results of the analysis by means of plotting the limits predicted in the above claims. Figure 3 shows the limits of the throughput-increase factor, γ_∞. Figure 4 shows the limits of the piconet energy-saving factor, $\varepsilon^{piconet}_\infty$. We note an interesting peak for the energy-saving factor in figure 4 at $K = 3$. This may suggest an energy-optimal size of $K = 3$ for the S-PAN piconet.

Observe that the difference between the higher and lower limits of figures 3 and 4 is quite significant and may increase or decrease with increasing K. The large difference is due to the conservative approach we used in estimating the worst-case scenario *overhead packets* in the S-PAN. Specifically, the overhead packets for the slaves' response in the S-PAN is assumed to be between one packet *per slave* and α (≤ 3) packets *per slave*. In the figures, $\alpha = 3$ is used for the lower limits.

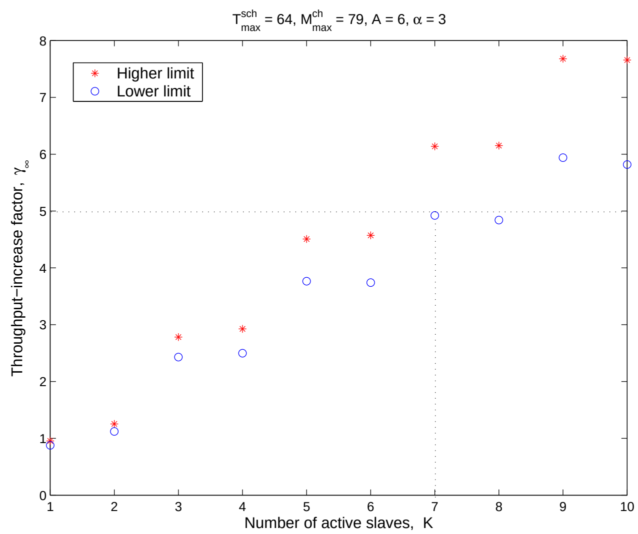

Fig. 3. The throughput-increase factor. Note that for $K = 7$, the maximum allowed number of active slaves in a Bluetooth piconet, the *lower limit* of the throughput-increase factor is almost 5.

Finally, we note that if we restrict $K \leq 7$, as in Bluetooth, then it is easy to modify the "polling", "response per slave", and "broadcast" packets to be single-slot packets. In this case, the S-PAN achieves the higher limits of figures 3 and 4 (for all $K \leq 7$). More importantly, note that the maximum delay for any slave to get its turn to access the channel in this case (i.e., when $K \leq 7$) is on the order of the length of the "overhead" time-slots in the S-PAN's frame, which is $P+R+B \leq 1+7+1 = 9$ time-slots. This is about $9 \times 625\mu s = 5.625$ ms. Even if we want to be conservative and assume another 9 time-slots in this interconnection period before a slave gets its chance to send, we have a maximum delay on the order of 11.25 ms.

IV. Concluding Remarks and Future Work

Motivated by some limitations of the current specification of Bluetooth, and recent amendments of the FCC rules governing the free-license ISM bands [2], we proposed the S-PAN, a switched PAN that outperforms the current Bluetooth piconet in throughput, delay, and power-fairness to the master.

Specifically, for throughput, it was shown that when $K = 7$, a S-PAN piconet using at most 4 channels concurrently in a single time-slot, may achieve a throughput-increase factor of about 5 (see figure 3).

An energy-saving in a S-PAN piconet compared to an equivalent Bluetooth piconet was shown. For example, it was

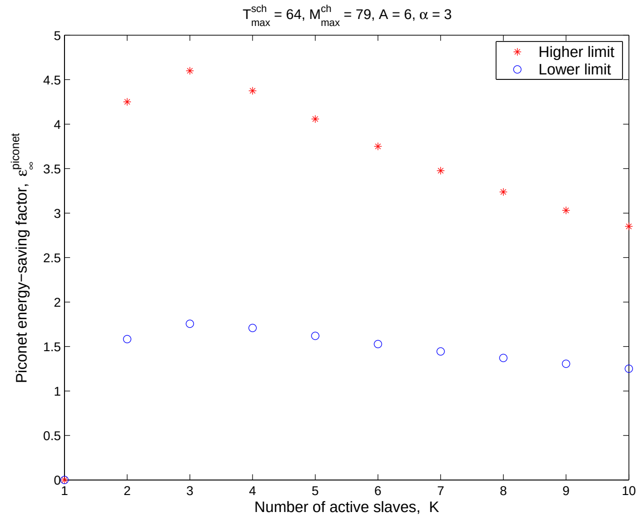

Fig. 4. The piconet energy-saving factor. The piconet energy-saving factor is identically zero for $K = 1$. To understand the meaning of this, recall that $\varepsilon_\infty^{piconet}$ is defined as the ratio of "unfairly" spent energy in the Bluetooth piconet to that spent in the S-PAN piconet. In the Bluetooth piconet, under the heavy load condition, no "unfair" energy is spent when $K = 1$. In the S-PAN piconet on the other hand, we defined the "polling", "response", and "broadcast" to be "unfairly" spent energy. Hence, the ratio for $K = 1$ is zero. This assumes that we do not make the exception of section III-A for the case $K = 1$. It should be noted that the master's energy-saving factor (not shown for space limitation) is about double that of the piconet's energy-saving factor when we assume $\mu = 1$. If we assume $\mu < 1$ as the usual case in practice, then $\varepsilon_\infty^{master}$ will be even higher.

shown that the "unfairly" expended energy of a Bluetooth piconet with 3 active slaves is about 4.5 times that of a S-PAN piconet under similar heavy load conditions (see figure 4). If we consider the energy-saving factor of the master alone, a factor of over 9 was shown to be possible when $K = 3$.

There are many open issues for future work. An example is considering the practical case in which not every node is within the transmission range of all other nodes. Another direction is the formation of scatternets under the S-PAN model. It is quite straightforward to form scatternets using the switch model. The master may act as a slave in another piconet and forward the traffic from its piconet to the master of the other piconet. Alternatively, a slave could act as a "bridge" or gateway to forward traffic to *multiple piconets*. We are in the process of developing these ideas more concretely.

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