An Efficient CDMA Scheme for Personal Area Networks

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***Abstract*— In this paper, we describe a scheme that allows N mobile nodes to talk with one another simultaneously 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. For the purposes of comparing our scheme to other proposals, we introduce a specific Bluetooth-based CDMA instance of the scheme that requires minimal changes to the current specification of Bluetooth. The Bluetooth-based CDMA scheme is shown to outperform the current Bluetooth specification in "efficiency" and in power consumption. Specifically, the Bluetooth-based CDMA piconet of the scheme is shown to achieve an "overhead ratio" as low as about 1% (with seven active slaves) compared to the possible overhead ratio of about 43% for an equivalent Bluetooth piconet. Furthermore, contrary to the Bluetooth piconet, the "overhead ratio" of the proposed CDMA piconet decreases as the number of active slaves in the piconet increases. It is also shown that the power consumed by a Bluetooth piconet is order of magnitudes (about 3.5 times and up to about 10 times, with seven active slaves) more than the power consumed by an equivalent piconet of the proposed scheme.**

I. Introduction

There are many proposals in the literature for multiaccess protocols that allow N mobile nodes to communicate with one another as an autonomous system [7]. However, providing hard Quality-of-Service (QoS) guarantees in the wireless environment has been the main limitation. For a survey see [4]. Most of these proposals provide best-effort service and some provide QoS guarantees via *reserved* channels. The reserved channels approach is inefficient for *bursty sources* since opportunities for transmissions will be wasted if the source assigned to the channel has no data, even if other sources have queued data ready for transmission. Therefore, we consider *statistical multiplexing* mechanisms that provide QoS guarantees in a wireless Personal Area Network (PAN) environment. The basic ideas and some results were first introduced in [1]. In this paper, we will present a new CDMA based proposal, and prove performance results regarding the "overhead ratio" (as defined below) and power consumption of the proposal. 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. We refer the reader to [5], [6] or the core specification [3] for a background or a comprehensive overview of Bluetooth, respectively.

This paper is organized as follows. Section I presents a motivation and a brief overview of salient issues. A summary description of the proposed scheme is given in section II. The main results of this paper is presented in section III. Concluding remarks are discussed in section IV.

II. A CDMA Based S-PAN

In this section, we first provide a brief overview of an efficient scheme for scheduling in PANs. This scheme, called Switched PAN (S-PAN) was introduced in [1]. We refer the reader to [1] for more details and other results. After the brief description of the general model, we introduce a Code Division Multiple Access (CDMA) instance of the general model.

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 constraint (Hd). Figure 1 shows a schematic diagram of the model.

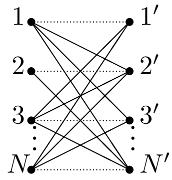

Fig. 1. A model in which the N mobile nodes and the wireless channel are modeled as an $N \times N$ switch. A dotted horizontal line indicates that a node i, on the left representing a transmitter, and the corresponding node i', on the right representing a receiver, are on the same physical mobile node.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

The "maximal" matchings in an NNBG (where NNBG is described in figure 1) that satisfy the Hd constraint are used to provide QoS guarantees in half-duplex ad-hoc networks. We call these "maximal" matchings, the *Half-duplex Constrained Maximal (HdCM) matchings*.

There are many approaches the central node may take to match requesting transmitters to their intended receivers. We assume a scheduling policy that uses CDMA and *any* HdCM matching between the transmitters and receivers. Maximal matchings are easier to compute than "maximum" matchings, however, the results also hold if a maximum matching is used since a maximum matching is also maximal (the converse is not true).

A Bluetooth-based CDMA S-PAN: We consider Bluetooth as a specific example of PAN networks against which we compare the performance of our scheme. To do so, we describe a proposed *specific* instance of the above *general* CDMA S-PAN scheme. For convenience, in the remaining of this paper, we will refer to this "Bluetooth-based instance of a CDMA S-PAN" simply as the CDMA S-PAN.

Consider an established Bluetooth piconet with K slaves and $N = K + 1$ nodes including the master. Assume that each node in the piconet is uniquely identified by a 1-byte address[1], where we assume that the all-zeros 8-bit address identifies the master. Applications for piconets with large number of slaves include industrial communications in factories, electronic wireless gaming, sensor networks applications, and others. The basic idea of the Bluetooth-based CDMA S-PAN scheme is to match requesting transmitters to their intended receivers without conflict.

In order to match communicating nodes without conflict, 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). The schedule could be computed for the next Bluetooth time-slot or for the next *several* time-slots. The three basic steps can be implemented in many different ways. The required communications in the first and third steps represent a communication *overhead* of scheduling. To minimize this overhead and to easily support time-sensitive data, we chose a polling scheme to implement the first step and a broadcast scheme (by the master) to implement the third step. The second step is implemented using either a maximum or a maximal matching as explained earlier.

The basic CDMA 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 are used for polling. Typically, $P = 1$, however, for reliability we may assume that a polling packet may be repeated a maximum of α_P time-slots. Second, the slaves respond. Assume that R time-slots are used for slaves' response. Note that in a CDMA system, all slaves may respond simultaneously (during the same time-slot) to the polling of the master. Hence, typically $R = 1$, however, for reliability we will assume that $1 \leq R \leq \alpha_R$, where α_R is a positive integer. Third, the master broadcasts a schedule. Assume that B time-slots are used for the schedule broadcast. Similar to the case of polling, assume that $1 \leq B \leq \alpha_B$. Let $A = P + B$. Lastly, the nodes are interconnected. Assume that I time-slots are 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}. Thus, $1 \leq I \leq T^{sch}_{max}$. Note that $F = P + R + B + I$.

[1]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.

Key Distinctions of a CDMA S-PAN Scheme: Contrary to the original S-PAN scheme of [1], in this CDMA S-PAN system, the number of time-slots used for slaves' response, R, is independent of the number of active slaves, K, and typically equals one time-slot. This is due to the fact that *all* slaves in a CDMA system may respond simultaneously (during the same time-slot) to the polling request by the master. However, as mentioned earlier, for reliability we will assume that $1 \leq R \leq \alpha_R$, where α_R is a positive integer. A second key difference between the original S-PAN system and a CDMA S-PAN system is that the number of active nodes in a piconet is not strictly limited to double the number of available channels. It is, however, limited based on the acceptable signal to noise ratio (SNR). Let the maximum number of allowable simultaneous communication links in a piconet be denoted by M_{max}. This parameter represents the maximum number of pairs that can communicate concurrently during a given time-slot. M_{max} in a CDMA system is a function of the acceptable SNR.

III. Efficiency of the CDMA S-PAN in comparison to Bluetooth

We will denote our scheme as the "CDMA" and compare it to a Bluetooth piconet, denoted by "BT" (for Bluetooth). Note that we are using the term "time-slot" interchangeably with the term "Bluetooth time-slot".

We need the following definitions to measure the "efficiency" of a CDMA S-PAN piconet and compare it to a Bluetooth piconet, under similar settings.

Definition 1: (Throughput-packets, overhead-packets, and overhead-ratio) 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 an "overhead-packet" and the packet transmitted by the master and received by the second slave as a "throughput-packet". In the CDMA S-PAN, all polling, slaves' response, and schedule-broadcast packets are defined as overhead packets.

We define the *overhead ratio* during an interval T time-slots, $\beta(T)$, as

$$\beta(T) = \frac{\text{Overhead packets during } T}{\text{Total transmitted packets during } T}. \tag{1}$$

And $\beta = \lim_{T\to\infty} \beta(T)$ if it exists.

Definition 2: (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 3: (Notational convention) Under the heavy load condition of definition 2, we denote the quantity β by β_∞, whether for a fixed duration T or in the limit.

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By "efficiency" of a piconet, we mean a measure of how many overhead packets are transmitted in a piconet over a long period of time. The less the number, the more efficient the piconet. This measure has a direct influence on both the "throughput" of the piconet and the *power efficiency*. For a fair comparison of efficiencies, it is critical to note that under the heavy load condition, we need to assume that the masters will not "starve" any active slave from sending to any other slave for a long period. This could happen, in BT piconet for example, if the BT master, having infinite load, only serves packets originating from the master or destined to the master from slaves. In this case, the Bluetooth piconet may achieve an overhead ratio close to zero. The comparison to a CDMA S-PAN piconet will not be fair since the CDMA S-PAN piconet does not have such a peculiar situation. Thus, for a fair comparison of overhead ratios, we need the assumption formalized in the next definition.

Definition 4: (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 each other node in the network. More precisely, under the heavy load condition of definition 2, 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, where $Z \leq K$ is a constant [2].

CLAIM 1: (Asymptotic overhead ratios under heavy load condition) Under the heavy load condition of definition 2, and the STS assumption of definition 4, we have

1) Overhead ratio for a Bluetooth piconet, β_∞^{BT}:

$$\frac{K-1}{2K} \leq \beta_\infty^{BT} \leq \frac{1}{2}. \tag{2}$$

2) Overhead ratio for a CDMA S-PAN piconet, β_∞^{CDMA}:

$$\frac{3}{3+\alpha^* T_{max}^{sch}} \leq \beta_\infty^{CDMA} \leq \frac{A+\alpha_R}{A+\alpha_R+\alpha^* T_{max}^{sch}}, \tag{3}$$

where α_R is the maximum number of time-slots per slaves' response, $\alpha^* = \min\{M_{max}, \lfloor \frac{K+1}{2} \rfloor\}$.

In order to prove claim 1, we need the following two lemmas, properties of HdCM matchings in NNBGs.

Lemma 1: (The maximum size of matchings satisfying the half-duplex constraint in an NNBG) The maximum size of any matching satisfying the half-duplex constraint in an NNBG is $|M^X| = \lfloor \frac{N}{2} \rfloor$, where N is the number of nodes of the NNBG.

Proof: Consider an NNBG with N nodes as in figure 1. Suppose M^X is any matching in the NNBG satisfying the half-duplex constraint. Pick any edge in M^X, say the edge matching node i (on the left side of figure 1) to node j' (on the right side of figure 1). This edge eliminates at least two other nodes from being matched in M^X, namely, node i', the horizontal node to i, and node j, the horizontal node to j'. Note that for any other edge in M^X, if it exist, say matching node k (on the left) to node l' (on the right), two other nodes (namely, k' and l) can not be matched in M^X. Clearly, id N is even, the size of any matching may not exceed $N/2$. If N is odd, note that at least one node will never be matched. Hence, $(N-1)/2$ is the maximum size of any matching when N is odd. Thus, in both cases the size of any matching in an NNBG satisfying the half-duplex constraint (maximal or other) may never exceed $\lfloor \frac{N}{2} \rfloor$. ■

Lemma 2: (Achievable size of half-duplex constrained matchings under heavy load condition) Under heavy load condition, a half-duplex constrained matching of size $\lfloor \frac{K+1}{2} \rfloor$ is always achievable.

Proof: An upper bound on the size of half-duplex constrained matchings of $\lfloor \frac{K+1}{2} \rfloor$ was established in lemma 1, where $K+1 = N$. It remains to show that it is achievable under heavy load. The fact that this is achievable follows by noting that under heavy load, we are guaranteed in the NNBG to have an edge from *each node* on the left side of figure 1 to *every node* on the right (except the horizontal edge). ■

Proof of Claim 1: Assume that T is large enough. We will consider the best and worst scenarios for a Bluetooth piconet and for a CDMA S-PAN piconet. First, consider a Bluetooth piconet. The best scenario (i.e., the least β_∞^{BT}) is when all packets from master-to-slaves *and* all packets from slaves-to-master are counted as throughput, a total of $2K$ packets. Note that there is a possibility for this to happen. Consider an epoch in T in which all nodes in the network sent at least one packet to each other node. In this epoch, at least a total of $K(K+1)$ packets are needed to be delivered to cover communications from each node to every other node in the network. Among these $K(K+1)$ packets, $2K$ packets are from master-to-slaves *and* from slaves-to-master. The remaining packets $K(K+1) - 2K = K(K-1)$ are from slave-to-slave, which will double in transmission by relaying them through the master. Thus, all slave-to-slave $K(K-1)$ packets constitute the overhead packets among the *total transmitted* packets of $2K + 2K(K-1)$. Assume that T is divided into epochs each one of length $2K + 2K(K-1)$ time-slots and each epoch covers the minimum set of packets for communication from every node to every other node in the network. Note that we may choose the epoch length conveniently as long as T is large enough. Assume that T contains α^{BT} epochs, where α^{BT} is a large positive integer. Then $\beta_\infty^{BT} \approx \frac{\alpha^{BT} K(K-1)}{\alpha^{BT}\{2K+2K(K-1)\}} = \frac{K-1}{2K}$, where α^{BT} is a large integer. The worst scenario for a Bluetooth piconet is when *half* of all transmitted packets is overhead packets. This could happen if the master serves slave-to-slave packets for the entire T. This completes the proof of (2).

Next, consider a CDMA S-PAN piconet under the same condition during the same large interval T. Assume that T is divided into epochs each one of length $A + R + I$ time-slots and each epoch covers the minimum set of packets for communication from every node to every other node in the network. Assume that T contains α^{CDMA} epochs, where α^{CDMA} is a large integer. Under heavy load condition, $I = T_{max}^{sch}$. In each interconnection time-slot (of the possible T_{max}^{sch} in an epoch), a maximal matching is used. Let the size of the maximal matching used be $|M^X|$. Under heavy

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load condition, by lemma 2, $|M^X|$ is the same for all epochs and $|M^X| = \lfloor \frac{K+1}{2} \rfloor$. However, if the maximum number of pairs allowed to be connected simultaneously in any time-slot, M_{max}, is less than the size of the matching, only M_{max} packets will be transported in a single time-slot. Thus, the total transported packets in an epoch is $A + R + \alpha^* T^{sch}_{max}$, where $\alpha^* = \min\{M_{max}, \lfloor \frac{K+1}{2} \rfloor\}$.

In the CDMA S-PAN, in each epoch, only $A + R$ are overhead packets by definition. Therefore, $\beta^{CDMA}_{\infty} \approx \frac{\alpha^{CDMA}(A+R)}{\alpha^{CDMA}\{A+R+\alpha^* T^{sch}_{max}\}} = \frac{A+R}{A+R+\alpha^* T^{sch}_{max}}$.

Equation (3) follows by noting the following. The best scenario for the CDMA S-PAN is when $A = P + B = 1 + 1 = 2$ and when the slaves' response takes a single time-slot. The worst scenario is when α_R (> 1) time-slots per slaves' response is used and $A > 2$. ■

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 CDMA 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 CDMA 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 5: (Energy-saving factors of the CDMA S-PAN piconet and of the master of the CDMA 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 $\mu = e_r/e_t$.

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

$$\begin{aligned} \varepsilon^{piconet}_{\infty}(T) &= \frac{(e_t + e_r)OP^{BT}(T)/T}{(e_t + e_r)OP^{CDMA}(T)/T} \\ &= \frac{OP^{BT}(T)/T}{OP^{CDMA}(T)/T}. \end{aligned} \quad (4)$$

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

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

$$\varepsilon^{master}_{\infty}(T) = \frac{[OP^{BT}_{master,t}(T) + \mu OP^{BT}_{master,r}(T)]/T}{[OP^{CDMA}_{master,t}(T) + \mu OP^{CDMA}_{master,r}(T)]/T}. \quad (5)$$

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 5, the *piconet energy-saving factor*, $\varepsilon^{piconet}_{\infty}$, is such that

$$e_1 \le \varepsilon^{piconet}_{\infty} \le e_2, \text{ where} \quad (6)$$

$$\begin{aligned} e_1 &= \frac{(K^2 - K)(A + \alpha_R + T^{sch}_{max})}{2K^2(A + \alpha_R)}, \\ e_2 &= \frac{(K^2 - K)(3 + T^{sch}_{max})}{6K^2}. \end{aligned}$$

Proof: Assume that T is large enough. Then we can consider the throughput packets in epochs of fixed length of time-slots in T. First, consider a BT piconet. Let the epoch length be[2] $2K^2$ time-slots, and assume that T contains α^{BT} epochs, where α^{BT} is a large positive integer. At best, all master-to-slave *and* slave-to-master packets, a total of $2K$ packets, are counted as throughput packets. The total of slave-to-slave packets is $K(K-1) = K^2 - K$. Note that the $K^2 - K$ packets will be counted as throughput packets when they are received by their destinations and also as overhead packets when transmitted by their sources. Therefore, asymptotically, $OP^{BT}/T \approx \frac{\alpha^{BT}(K^2-K)}{\alpha^{BT}(2K^2)}$.

Second, consider an equivalent CDMA S-PAN piconet over the same time interval T. Let the epoch length in this case be $A + R + T^{sch}_{max}$, and assume that T contains α^{CDMA} epochs, where α^{CDMA} is a large positive integer. Note that we may choose the epoch length conveniently as long as the number of epochs in T is large enough. The overhead packets in CDMA S-PAN in an epoch is by definition $A + R$. Hence, asymptotically, $OP^{CDMA}/T \approx \frac{\alpha^{CDMA}(A+R)}{\alpha^{CDMA}(A+R+T^{sch}_{max})}$.

Therefore, $\varepsilon^{piconet}_{\infty} \approx \frac{OP^{BT}/T}{OP^{CDMA}/T} \approx \frac{(K^2-K)(A+R+T^{sch}_{max})}{2K^2(A+R)}$. Equation (2) follows by noting that the best case scenario for the CDMA S-PAN is when the response $R = 1$ instead of $R = \alpha_R$ and when $A = 2$, the minimum possible. ■

Corollary 1: (of claim 2) (Asymptotic comparison of energy overhead of masters of the piconets) Under heavy load condition and the assumptions of definition 5, the *master energy-saving factor*, $\varepsilon^{master}_{\infty}$, is such that

$$e_3 \le \varepsilon^{master}_{\infty} \le e_4, \text{ where} \quad (7)$$

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

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\begin{aligned}
e_3 &= \frac{(1+\mu)(K^2-K)(A+\alpha_R+T_{max}^{sch})}{2K^2(A+\mu\alpha_R)}, \\
e_4 &= \frac{(1+\mu)(K^2-K)(3+T_{max}^{sch})}{2K^2(2+\mu)}.
\end{aligned}
$$

Proof: The proof is a direct result of claim 2 and application of the definition in (5). Care must be taken in separating the overhead packets *transmitted by the master* which expend e_t units of energy and the overhead packets *received by the master* which expend e_r. ■

A. Discussion of the results

We discuss the results by means of plotting the limits predicted in the above claims (see figures 2 and 3). Figure 2 shows the significance of the results. A key feature of the proposed CDMA scheme is that the scheme becomes more efficient (in terms of overhead packets) as the number of active slaves increases in the piconet. As shown in figure 2, this is the opposite of the behavior of the current specification of Bluetooth. As a specific numerical example, with seven active slaves in the piconet, the Bluetooth specification results in about 43% overhead ratio while the proposed scheme achieves a low overhead ratio of only about 1%.

Observe that the difference between the higher and lower limits is quite significant, as exemplified by figure 3. This is due to the conservative approach we used in estimating the worst-case scenario *overhead packets* in the CDMA S-PAN. Specifically, the overhead packets for the slaves' response in the CDMA S-PAN is assumed to be between one packet *per slaves' response* and α_R packets *per slaves' response* ($\alpha_R = 3$ was used to produce the figure). Similar conservative estimate was used for the "polling" and "broadcast" by the master ($\alpha_P = 3$, and $\alpha_B = 3$ were used to produce the figure). Clearly, this constitutes a large difference in estimating the overhead packets.

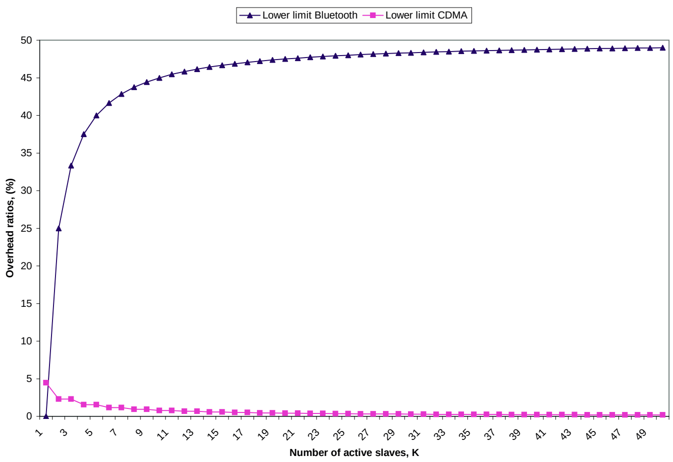

Fig. 2. The overhead ratios (lower limits of equations (2) and (3)). Note that the overhead ratio of the CDMA S-PAN decreases as K increases while the overhead ration of Bluetooth increases as K increases.

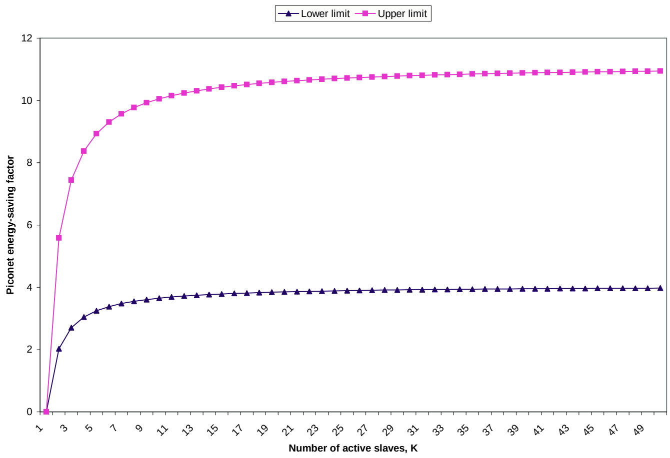

Fig. 3. Piconet energy-saving factor.

IV. Concluding Remarks

A description of a new CDMA based proposal for a PAN architecture was presented. The main objectives of the study were to reduce the number of unnecessarily exchanged control packets between the member nodes of a PAN and to reduce the power consumption of all active nodes. The control packets are defined to be "overhead" packets.

It was proved in this paper that the "efficiency" (in terms of overhead packets) of the proposed scheme when compared to the current Bluetooth specification is significantly superior. Specifically, it was shown that an overhead ratio of communication which may reach 43% in a Bluetooth piconet with seven active slaves could be reduced to the order of only 1% in the proposed scheme, as demonstrated in figure 2.

In addition, the power consumption of a typical Bluetooth piconet was shown to be several folds the power consumption of an equivalent (in number of nodes and traffic pattern) piconet of the proposed scheme. Specifically, it was shown that the power consumed by a Bluetooth piconet of seven active slaves is about 3.5 times (and may reach more than 9 times) the power consumed by an equivalent piconet of the proposed scheme (see figure 3).

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