Cooperative Transmission Range Doubling with IEEE 802.15.4

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***Abstract*— In battery-driven multi-hop wireless sensor networks, the most highly burdened relay nodes, or bottleneck nodes, will die first. These deaths eventually partition the network and trap valuable battery energy in the network. In a multi-hop wireless sensor network that must harvest energy from weak energy sources, the nodes that are one hop away from the Sink must sometimes shut down to harvest, so they limit the access that the rest of the network has to the Sink. One way to lengthen the time-to-partition or increase access to the Sink is to exploit some of the would-be-trapped energy to do cooperative transmission (CT) range extension to hop over the bottleneck node and communicate directly with the next-hop node (e.g., the Sink).To do this, approximate range doubling is necessary. In this paper, we investigate the potential for range doubling over Rayleigh faded channels of four CT schemes that are compatible with the IEEE 802.15.4 standard. We consider the effects of path loss disparities and how many cooperators are necessary for each CT scheme.**

Keywords-component; wireless communications; cooperative transmission; IEEE 802.15.4.

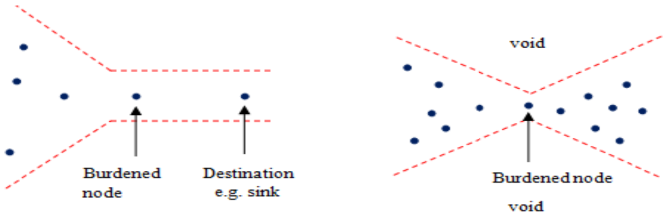
I. INTRODUCTION

Cooperative transmission (CT) is a virtual array technique in which multiple single-antenna radios transmit versions of the same message through uncorrelated fading channels to exploit transmit diversity. The versions are then combined at the receiver to provide an SNR improvement, based on transmit diversity and array gains [1]. The SNR advantage can be used to lower the error rate, extend range, or reduce transmit power. IEEE 802.15.4 is a standard [2] designed for low data rate, low power consumption, and low cost applications. With the spreading of low-rate wireless personal area network (WPAN) applications, CT schemes that conform to 802.15.4 are increasingly studied [3,4,5]. In this paper, we focus on CT range extension techniques for doubling range in IEEE 802.15.4 network.

CT range extension can mitigate certain problems in multi-hop wireless sensor networks. For example, nodes near the sink will be heavily burdened because they must relay the packets from the other nodes in the network. In battery-driven networks, these nodes will die first and eventually partition the network [6], and in networks that do energy harvesting and duty cycling, these nodes limit access to the sink node [7]. The protocols presented in [6] and [7] apply CT range extension to extend network life [6] or increase access to the sink [7] by exploiting the energy of less-burdened nodes to "hop over" the more burdened or "bottleneck" node. When the hop is directly to the sink, the local topology has a "funnel" shape, as shown in Fig.1a. When the hop is to multiple nodes on the other side of the burdened node, the local network has a "bow-tie" shape, as shown in Fig.1b. The bow-tie shape can occur in random or constrained deployments; the occasional use of CT in this case may save energy compared to routing around the voids on either side of the burdened node.

To assess the effectiveness of a CT-based energy balancing scheme, a realistic model of the energy cost of doing CT is needed. As a first step towards an energy model, this study aims to determine how many 802.15.4 nodes would be required to approximately double range for both funnel and bow-tie networks. Such knowledge is also helpful in the design of CT recruiting and Network Layer protocols that would implement CT on 802.15.4 radios. Because co-located cooperators cannot be expected in a typical deployment, the study also considers the effects of disparities in the path losses when cooperators have significant separation.

Several other authors [3][4][5][8][9] have considered CT either for or based on 802.15.4 networks, however, none of these have focused on range extension, therefore their results will not enable us to determine how many nodes are necessary to do range doubling. Instead, these papers focus on reducing packet loss or increasing throughput. The "Poor Man's SIMO System" of [3] allows for several standard-compliant diversity combining techniques, such as receiver selection diversity and post-detection packet combining; we consider these combining techniques in this paper. Other authors have proposed diversity techniques that require either (1) added hardware, e.g., they combine multiple transceivers on one node [4][5], (2) concurrent transmission, i.e., the simultaneous and synchronous transmissions of cooperating nodes, such as is required for the Alamouti Space Time Block Code, which is not consistent with the IEEE 802.15.4 standard [8], or (3) modification to the RF integrated circuit (RFIC) to enable alternative physical layer signal processing [9]. In contrast to [4], [5], [8], and [9], we wish to consider schemes that would require only software modification to off-the-shelf 802.15.4 nodes. Compared to [3] and [5] which do only receive diversity, we combined transmit diversity with received diversity, forming a multiple input multiple output (MIMO) cluster to cluster communication. MIMO cluster to cluster communication was not addressed in any of the previous works mentioned above. Particularly, [3], [5], and [9] consider the single input multiple output (SIMO) case whereas [8] considers the multiple input single output (MISO) case. We also consider transmit repetition which is not included in [3][4][5][8][9].



(a) "Funnel" (b) "Bow-tie"

Figure 1. (a) A "funnel" network, (b) A "bow-tie" network

II. SYSTEM MODEL

This section first introduces the single-input-single-output (SISO) channel model and the bit error rate (BER) model of the 2.4GHz PHY of IEEE 802.15.4. Description of various CT schemes including both the 802.15.4-compliant and the optimal versions is given next. Finally, we provide our methods to analyze the range extension performance of each CT scheme in both the co-located scenario and path loss disparities scenario.

A. The SISO BER model

In post-detection CT, transmissions are first made over SISO links, where bit errors can happen when the bits are detected in a SISO receiver[1]. Next, if SIMO diversity combining is being done, the bits detected by each receiver (some of which may have been detected erroneously), for a given packet, are forwarded to a node that will combine the detected bits from multiple SISO links to produce a final set of bits associated with the packet. For post-detection MIMO CT, a single receiver separately detects and stores the bits transmitted by each transmitter, then combines and re-detects those bits, and then forwards the re-detected bits to a node that will combine the re-detected bits from each receiver. When simulating diversity combining, we use a Bernoulli random number generator to determine which bits are in error in each SISO link, such that the probability of bit error is equal to the calculated value of the SISO BER for that link. Therefore, the SISO BER model is the foundation of our approach.

We will refer to the cooperators on the source side of the bottleneck as the "transmit cooperators," and cooperators on the destination side as "receive cooperators." Let h_{ij} be the complex-valued channel gain between the j-th transmit cooperator and the i-th receive cooperator, and let h_{ij} be the ij-th element of the channel gain matrix H. We assume flat Rayleigh fading, so $|h_{ij}|$ is Rayleigh distributed with $\mathrm{E}\left\{|h_{ij}|^2\right\} = 1$, and we assume sufficient node separation so the channel gains are independent. The *instantaneous* received SNR of the ij-th SISO link is expressed as $SNR_{ij} = |h_{ij}|^2\overline{SNR}_{ij}$, where $\overline{SNR}_{ij}$ is the average received SNR of the ij-th SISO link.

Conditioned on a particular fading outcome for the ij-th SISO channel, we assume the BER model for the AWGN channel as specified in the 2.4GHz PHY of the standard, for 16-ary offset-quadrature phase shift keying (O-QPSK) [2]:

$$BER_{ij} = \frac{8}{15} \times \frac{1}{16} \times \sum_{k=2}^{16} (-1)^k \binom{16}{k} e^{20\left(\frac{1}{k}-1\right)SNR_{ij}}, \quad (1)$$

where BER_{ij} is the BER of the ij-th SISO channel.

Figure 2. A linear network topology

In the SISO or non-CT case, the packet error rate (PER) at the receiver is computed directly from the BER as $PER = 1 - (1 - BER)^N$, where N is the packet length in bits. There will be one PER value for each fading outcome. Let $\overline{PER}$ be the PER when averaged over the Rayleigh fading outcomes. Let Λ be a certain acceptable value for $\overline{PER}$. Then we define $\overline{SNR}_{SISO}$ to be the minimum $\overline{SNR}$ that yields $\overline{PER} \leq \Lambda$.

In order to model SISO links with different values of path loss, we consider a linear local network with n transmit cooperators denoted as T1, T2, etc. and m receive cooperators denoted as R1, R2, etc. as shown in Fig. 2. T1 and R1 are respectively the closest previous-hop node and the closest next-hop node of the bottleneck node, which is represented as the black circle. All other cooperators are further away from the bottleneck node. The to-hop-over distance, denoted as d_{center} in this figure, is the distance between T1 and R1. Let d' be the distance between two adjacent transmit cooperators or receive cooperators, which is related to d_{center} as $d' = \gamma d_{center}$, where $\gamma > 0$. Hence, we can control the path loss disparities between different TX-RX pairs using the factor γ. We also consider the "co-located" case, where $\gamma = 0$. By "co-located," we do not mean that the radios are all in exactly the same location. Rather, we mean that they are close enough that we can assume equal path loss between any one of them and any node in the other cluster they are communicating with, yet they have sufficient spacing between them (e.g., at least one half wavelength in a rich scattering environment) to be able to assume independent Rayleigh fading.

B. Computing $\overline{PER}$ for different types of CT

In this section, we consider various 802.15.4-compliant CT range extension schemes that can be employed in both the "funnel" and "bow-tie" networks as depicted in Fig.1. For comparison purposes, we also consider some optimal *pre-detection* combining schemes[2]. We will use the notation $nX \cdot mY$ to mean that CT scheme X is used with n transmit cooperators and CT scheme Y is used with m receive cooperators. The dot $\cdot$ in the notation represents the bottleneck node. We describe the diversity schemes detail below, but as a notation example, $3S \cdot 2C$ means relay selection (S) over 3 transmit cooperators and receive diversity packet combining (C) with 2 receive cooperators; $4S \cdot$ means relay selection over 4 transmit cooperators, with only one receiver.

We compare different CT schemes by finding the maximum normalized distance between the transmit cooperators and the receive cooperators for each scheme, such that $\overline{PER} \leq \Lambda$. The way $\overline{PER}$ is computed depends on the type of CT. Therefore, in this section we explain how we compute $\overline{PER}$ for each type of CT.

Selection (S): Selection is illustrated in Fig.3, where the source S transmits its packet, and each cooperator T1, T2, T3, and T4 receives a version of that packet. We assume the source

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[1] 802.15.4 receivers first detect symbols and then map the detected symbols to 4-bit words [2].

[2] Optimal pre-detection diversity combining schemes are not possible with off-the-shelf 802.15.4 nodes.

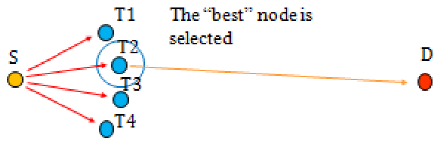

Figure 3. Relay selection

and the relays are close enough that each cooperator receives an error-free copy of the packet. Many relay selection techniques have been studied. In general, these schemes aim to select the relay candidate that gives the best performance at the destination. For each fading outcome, we select the b-th cooperator when b is the value of j that minimizes $PER_{0j} = 1-\left(1-BER_{0j}\right)^N$. BER_{0j} is the BER of the SISO link between Tj and the destination, which has index 0. $\overline{PER}$ is the average of the values of PER_{0b}, over the different outcomes of $\boldsymbol{h}_{0:}$, which is the vector of the complex channel gains between the set of transmit cooperators and the destination.

Receive Diversity Packet Combining (C): We use the Poor Man's SIMO System cooperative post-detection packet combining protocol presented in [3], which does distributed array reception on hard decoded data. Each of m receivers receives an independently faded version of the same packet from a transmitter T, with index 0. Let the received, detected data at the i-th receiver be denoted as D_i. In our simulations of Poor Man's SIMO, we induce random bit errors in D_i according to BER_{i0}. [3] considers three types of post-detection combining: selection, equal-gain (EG), and maximal-ratio (MR). For EG and MR, the combined packet is

$$D^{EG/MR} = \begin{cases} D_i, & if\ the\ data\ is\ error\ free \\ S\left(\frac{1}{m}\sum_{i=1}^{m} w_i D_i\right), & otherwise \end{cases},$$

where S(.) performs binary thresholding (threshold = ½), $w_i = 1$ for EG, and $w_i = 1-\beta_{i0}$ for MR, where β_{i0} is the BER estimate obtained in the i-th receiver from a Channel State Information measurement-based BER model [3][10]. As shown in the experimental implementation results in [3], EG, which has the lowest complexity among the three post-detection combining techniques since it does not rely on a BER model, gives the best performance in terms of packet error rate. Therefore, we only evaluate EG in our simulations. The optimal *pre-detection* version of receive diversity packet combining is Maximal Ratio Combining (MRC), which weights the soft outputs of each channel with h_{i0}^* before adding, followed by detection [11]. In our simulations, we let l_p be the number of erroneous combined packets for the p-th fading trial. Then, $\overline{PER}=\left(\sum_{p=1}^{N_{trials}} l_p\right)/\left(N_{pkts}N_{trials}\right)$, where N_{trials} is the number of fading trials and N_{pkts} is the total number of packets transmitted by T per trial. For the optimal case, $\overline{PER}$ is calculated as in the non-CT case, with SNR replaced with $SNR_{MRC} = \sum_{j=1}^{m} SNR_{j0}$.

Transmit Selection and Packet Combining: This scheme, denoted as $S \cdot C$, implements selection on the transmit side and Receive Diversity Packet Combining on the receive side. Our simulation method is as follows. For each fading outcome, we let each transmit cooperator transmit individually N_{pkts} packets. Let l_p^j be the number of erroneous combined packets for the p-th fading trial when only the j-th transmit cooperator transmits. We select the b-th transmit cooperator when $b = arg \min_{j=1,\ldots,n} l_p^j$. Then, $\overline{PER} = \left(\sum_{p=1}^{N_{trials}} l_p^b\right)/\left(N_{pkts}N_{trials}\right)$. The optimal case, Transmit Selection and Optimal Receive Combining ($S \cdot MRC$), employs selection on the transmit side and MRC on the receive side. In this optimal version, the selected transmit node's channel vector has the largest norm. By saying the channel vector of the j-th transmit cooperator, we mean the j-th column of H, denoted as $\boldsymbol{h}_{:j}$.The instantaneous received SNR is given as $SNR_{Sel\_MRC} = \sum_{i=1}^{m} SNR_{ib}$, corresponding to the b-th selected transmit cooperator. $\overline{PER}$ is calculated as in the non-CT case, with SNR replaced with SNR_{Sel_MRC}.

Transmit Repetition and Packet Combining (R·C): On the transmit side, the cooperators transmit copies of the same packet, one at a time. Each receive cooperator does local packet combining on its received copies, and then forwards its own combined packet to a node designated to combine the locally combined packets. This designated node could be one of the receive cooperators. Let l_p be the number of erroneous combined packets for the p-th fading trial. Then, $\overline{PER}=\left(\sum_{p=1}^{N_{trials}} l_p\right)/\left(N_{pkts}N_{trials}\right)$. The optimal pre-detection version of this scheme, MIMO with optimal diversity, denoted as MIMO-OD, achieves SNR improvement by the factor of σ_1^2, where σ_1 is the maximum singular value of H [12]:

$$SNR_{MIMO-OD} = \sigma_1^2 \overline{SNR}_{11}.$$

Optimum case $\overline{PER}$ is calculated as in the non-CT case, with SNR replaced with $SNR_{MIMO-OD}$.

C. Range Extension Ratio

In the co-located case, we determine the minimum average received SNRs, $\overline{SNR}_{SISO}$ and $\overline{SNR}_{CT,colo}$, that correspond to the SISO and the co-located CT cases, respectively, such that $\overline{\text{PER}} \leq \Lambda$. Let d_{SISO} and $d_{CT,colo}$ be the corresponding maximum distances (ranges) for the SISO and the co-located CT cases. Then we define the range extension ratio as

$$\beta = \frac{d_{CT,colo}}{d_{SISO}} = \left(\overline{SNR}_{SISO}/\overline{SNR}_{CT,colo}\right)^{1/\alpha}, \qquad (2)$$

where α is the path loss exponent. We use α = 3.3, which is consistent with the 2.4GHz PHY of the IEEE 802.15.4 standard, for the case when all transmitter-receiver distances are greater than 8m [2].

D. Maximum path loss disparity

In this section, we assume T1 and R1 are separated by $2d_{SISO}$, therefore $d_{center} = 2d_{SISO}$ in Fig. 2. We look for the maximum value of γ, γ_{max}, at which the system still yields a $\overline{PER}$ not exceeding the required threshold.

We assume that all nodes have the same transmit power, the same antenna gain, and the same receiver noise power. It follows that the average SNR received at R1 from T1 can be represented as

$$\overline{SNR}_{11} \triangleq \frac{1}{2^{\alpha}} \overline{SNR}_{SISO}. \qquad (3)$$

Similarly,

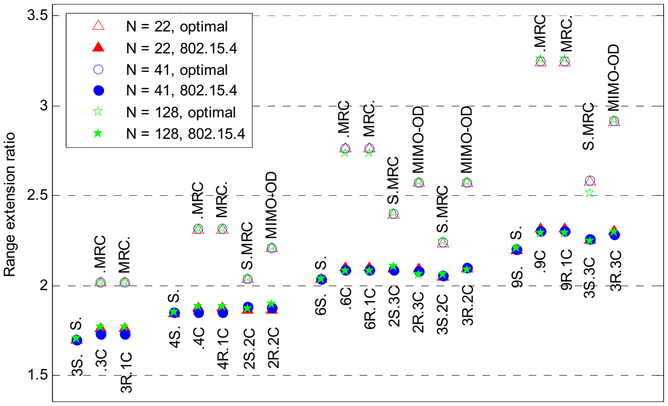

Figure 4. Range extension ratios of CT schemes in co-located case

$$\overline{SNR}_{ij} = \left(\frac{1}{1+\gamma(i+j-2)}\right)^{\alpha} \overline{SNR}_{11}. \tag{4}$$

In order to find γ_{max}, we find the $\overline{PER}$'s for different values of γ using the approach described in Section II-B and then use linear regression to find a straight-line model that fits the population of samples of $(\overline{PER}, \gamma)$. Based on this linear model, γ_{max} is the value of γ that yields $\overline{PER} = \Lambda$.

III. SIMULATION RESULTS

In this section, we will investigate the range extension performance of each CT scheme in two scenarios: no path loss disparities and with path loss disparities. We choose EG to do post-detection packet combining. Specifically, if any of the receive versions is error-free (in practice, determined by CRC check), selection diversity is employed to pick that error-free version as the combined packet; otherwise, EG is employed to try to correct the errors from all the erroneous received copies.

The channel is assumed to be constant over an interval of 1000 packets. For the 802.15.4-compliant schemes except $S\cdot$, PER is estimated based on those 1000 packets, using the methods of the previous section. The PER is then averaged over K channel realizations, where $K = 200{,}000$ for $S\cdot$ and $K = 2000$ for other CT schemes. An average packet error rate of $\Lambda = 0.1$ is the threshold.

A. No path loss disparities (co-located case)

When all the transmit cooperators are co-located and so are the receive cooperators, there are no path loss disparities between all the SISO links. The range extension performance of various CT schemes in this case is depicted in Fig. 4, where we analyze the CT schemes for three different values of packet length N: 22 bytes as specified in [2], 41 bytes as used in [3], and 128 bytes. Note that CT schemes of the same diversity order are grouped together in the figure. For each packet length N, the lower group of symbols represents the 802.15.4-compliant CT schemes mentioned in Section II and the upper group of symbols represents the corresponding optimal CT schemes. As we can see from the figure, there is not much difference between the three different values of packet length.

From Fig.4, we can figure out how many cooperators are needed for each scheme to double the range in co-located case, in other words, to hop over the bottleneck node and communicate directly with the next-hop node. These will be cases where the symbols are above the horizontal line representing a range extension ratio of 2. Many 802.15.4 compliant schemes exceed the doubled range and require different number of nodes. For example, $6S\cdot$, $\cdot 6C$ and $6R\cdot 1C$ require a total of 7 nodes, $2S\cdot 3C$, $2R\cdot 3C$, $3S\cdot 2C$, and $3R\cdot 2C$ require a total of 5 nodes, $9S\cdot$, $\cdot 9C$ and $9R\cdot 1C$ require a total of 10 nodes whereas $3S\cdot 3C$ and $3R\cdot 3C$ require a total of 6 nodes. Therefore, a minimum of 5 nodes is required to more than double the range.

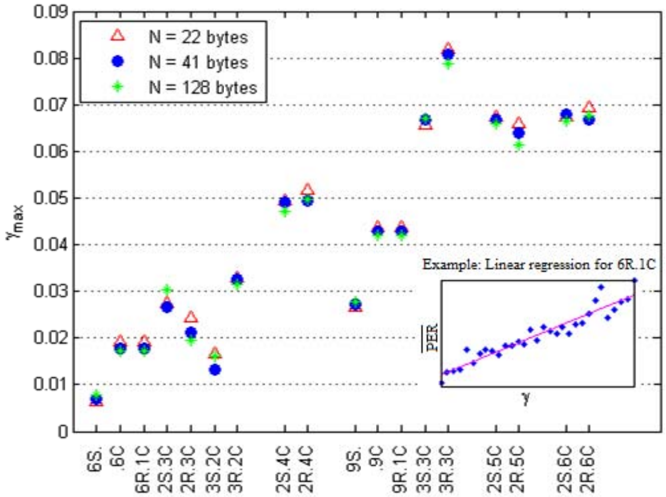

Figure 5. Maximum tolerable path loss disparities of 802.15.4-compliant CT schemes

Pre-detection optimal combining performs better than post-detection combining. Therefore, both $R\cdot C$ and $S\cdot C$ suffer from post-detection combining penalty as compared with their corresponding optimal versions, MIMO-OD and $S\cdot MRC$, which employ pre-detection packet combining MRC at RX side. However, since $S\cdot C$ and $S\cdot MRC$ usually select the same transmit nodes, the gaps in their range extension performance are smaller than the gaps between $R\cdot C$ and MIMO-OD. Particularly, $S\cdot$ yields the same range extension performance with its optimal version since they always select the same transmit nodes.

Except $S\cdot$, for a given diversity order, the gaps between optimal and compliant cases are smaller when cooperation is employed on both transmit and receive sides than only one side. In other words, CT is most efficient when there are some nodes on each side.

Another observation is that for a given system size, i.e., for a given number of transmit cooperators and receive cooperators, where the number of transmit cooperators is greater than 2, $R\cdot C$ outperforms $S\cdot C$ in term of range extension. This is because although both exploit receive combining diversity, $R\cdot C$ has a benefit from majority voting on every bit whereas $S\cdot C$ does not, so a locally combined packet can be correct even if all SISO detected versions had some errors. However, it is interesting to note that $2R\cdot mC$ does not always perform better than $2S\cdot mC$ in term of range extension, although the difference in range extension ratio between $2S\cdot mC$ and $2R\cdot mC$ is very small. This can be explained as follows. In $2R\cdot mC$, local EG packet combining is employed over two received versions for each transmitted packet at each receive cooperator. The tie-voting for each bit position will be correct with probability of 50% *if* one received packet has the correct bit and the other has the incorrect bit at the same bit position. This 50% probability of error diminishes the advantage of $2R\cdot mC$ over $2S\cdot mC$. Another interesting case is when a CT scheme is implemented in only either transmit side or receive side. $nR \cdot 1C$ and $\cdot nC$ have the same range extension performance since both of them do receive diversity packet combining over n received versions for each transmitted packet. When $n > 2$, since $nR \cdot 1C$ has a benefit from majority voting on every bit whereas $nS \cdot$ does not, $nR \cdot 1C$ outperforms $nS \cdot$, and so does $\cdot nC$.

B. With path loss disparities

Since the co-location assumption is not realistic, we have to take into account the path loss disparities between different transmit cooperator - receive cooperator pairs, which diminish diversity gain. We consider the linear network topology depicted in Fig. 2. In this figure, T1 and R1 are each only one hop away from the bottleneck node, the other cooperators are more than one hop away from the bottleneck node. Apparently, a necessary condition for a CT scheme to double the range in the presence of some path loss disparities is that it yields more than range doubling in the co-located case. Therefore, we will consider only the CT schemes with $\beta > 2$.

Fig. 5 shows the maximum tolerable path loss disparities of various 802.15.4 compliant CT schemes. "Maximum tolerable" means that $\overline{PER}$ does not exceed the required threshold while range doubling in the middle is still achieved, i.e. the cooperation can hop over the bottleneck node and communicate directly with the next-hop node or the receive-side cluster. As described in Section II-D, we found γ_{max} by first doing a linear regression on the $\overline{PER}$ values, as a function of γ (an example is shown in the inset), and then using the regression line to find γ_{max}. Note that CT schemes of the same diversity order are grouped together in the figure.

As we can see, all cases shown allow some path loss disparity and balanced topologies allow the most disparity. In the co-located case, we saw that certain CT configurations outperformed other CT configurations; these same certain CT configurations also tend to tolerate more path loss disparity than the other configurations. Specifically, $nR \cdot 1C$ and $\cdot nC$ both tolerate more path loss disparity than $nS \cdot$, $nR \cdot mC$ tolerates more path loss disparity than $nS \cdot mC$ when $n > 2$, and $2R \cdot mC$ does not always tolerate more path loss disparity than $2S \cdot mC$. In the co-located case, we determined that a minimum of five nodes are necessary to double the range. In the path-loss-disparities case, the best five-node configuration, $3R \cdot 2C$, gives 3% path loss disparity, and the best six-node configuration, $3R \cdot 3C$, gives 8% path loss disparity. For example, for a SISO range of 25m, which is the middle value of indoor ranges for MICAz [13], an off-the-shelf 802.15.4 radio, we have $d_{center} = 50$m, therefore 5 nodes can support 1.5m and 6 nodes can support 4m separation between adjacent cooperating nodes. While these are short distances in a linear network, the implied differences in SISO ranges are possible in an indoor two-dimensional deployment.

In this figure, we also observe that the three values of packet length, which are 22, 41, and 128 bytes, give similar values of γ_{max}, for each type of CT scheme. We observe that the CT schemes do not have the same ordering for different values of frame length, which we attribute to statistical errors. When we investigated this, we found that the PER distribution has an extreme bimodal shape (many outcomes at zero and at one), which implies that PER is approximately a step function of SNR. We think this makes the variance of the sample mean of the PER high, which leads to slight variations in γ_{max}, even though we generated a very large number of fading outcomes.

IV. CONCLUSION

We have investigated four CT schemes which are consistent with the IEEE 802.15.4 standard, namely, Transmit Selection, Receive Diversity Packet Combining, Transmit Selection and Packet Combining, and Transmit Repetition Packet Combining, to extend the transmission range with the purpose of hopping over the bottleneck node and communicating directly with the next-hop node (e.g., the sink), thereby reducing the burden of the bottleneck nodes in the network and prolonging their lifetime or the time-to-partition of the network. In order to do this, approximate range doubling is necessary. In the no-path-loss-disparities scenario, we found out that a minimum of five 802.15.4 nodes are required to more than double the range. In the path-loss-disparities scenario, we found that more nodes are needed to support moderate path loss disparities. We determine that balanced topologies are most efficient in the first scenario and tolerate more path loss disparities in the second scenario.

For future work, we will consider two-dimensional networks and MR combining in the path-loss-disparities case. The results of this study, together with a CT MAC protocol, can form the basis of a CT energy model.

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