HIGH QUALITY END-TO-END LINK PERFORMANCE

Adaptive Distributed MIMO Multihop Networks with Optimized Resource Allocation

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Recently, there has been an increasing interest in applying traditional point-to-point multiple-input multiple-output (MIMO) techniques to multihop wireless relaying networks to support higher end-to-end (e2e) data rates and to provide a better user experience [1]–[5]. By the concept of virtual antenna array (VAA), spatially separated relaying nodes can utilize the capacity improvements offered by MIMO transmission techniques. For example, the application of distributed space-time codes was proven in [5] to significantly improve the data rate in multihop networks. Figure 1 depicts a distributed MIMO multihop network, where one source communicates with one destination via a number of relaying VAAs in multiple hops. Spatially adjacent nodes in a VAA receive data from the previous VAA and relay the message to the consecutive VAA until the destination is reached.

The general concept of distributed MIMO multihop communication systems has been analyzed in [4] and [5],

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where explicit resource allocation strategies were introduced to maximize the e2e data throughput over ergodic fading channels under the assumption of fixed total transmit power. For the same power constraint, an allocation strategy for minimizing the error rate is given in [6]. However, as the majority of today's wireless communications happen over slow-fading channels, i.e., nonergodic in the capacity sense, the consideration of the e2e outage probability is of higher practical relevance. In addition, approaches for minimizing the transmit power are desired. The task of minimizing the total power while meeting a given e2e outage probability constraint has been analyzed in [7]–[9], and a near-optimum closed-form solution has been derived in [9].

As discussed in [2], the drawback of fixed decode-and-forward transmission is that it requires full decoding at all relays. Thus, a multihop connection is considered to be in outage if any relay cannot decode the message correctly. The e2e performance is then determined by the worst relay link in the network. A similar assumption has also been made in [7]–[9] in terms of e2e outage probability and in [4] in terms of ergodic capacity. This strong assumption degrades the e2e performance drastically. Thus, a simple adaptive decode-and-forward scheme for distributed MIMO multihop networks that avoids this drawback will be considered here.

The aim of this article is to present the adaptive transmission scheme and propose resource allocation strategies for meeting the e2e outage probability constraint over slow-fading channels. This is achieved by optimally assigning resources in terms of fractional time and transmission power to the hops on the basis of network geometry, i.e., the number of nodes per VAA and the distances of the hops. To this end, the e2e outage probability is derived. Based on this result, the power allocation problem and the joint power and time allocation (JPTA) problem are formulated. As shown in [10]–[13], the occurring optimization problems are convex and therefore be solved by common optimization tools.

Adaptive Transmission System

Transmission Strategy

We consider a K-hop network with t_k transmit nodes and r_k receive nodes at hop k, i.e., $t_{k+1} = r_k$. Several relays are grouped to a VAA at each hop to apply a distributed space-time code. The data is then transmitted from the source to the destination by $K-1$ VAAs. It is assumed that no interference between the hops occur. Thus, the bandwidth or time has to be divided into nonoverlapping parts for each hop such that, at any time, they are occupied by only one hop, i.e., frequency division multiple access (FDMA) or time division multiple access (TDMA), respectively. Without loss of generality, the TDMA-based adaptive scheme will be considered here for explanation.

SPATIALLY SEPARATED RELAYING NODES CAN UTILIZE THE CAPACITY IMPROVEMENTS OFFERED BY MIMO TRANSMISSION TECHNIQUES BY THE CONCEPT OF VIRTUAL ANTENNA ARRAY.

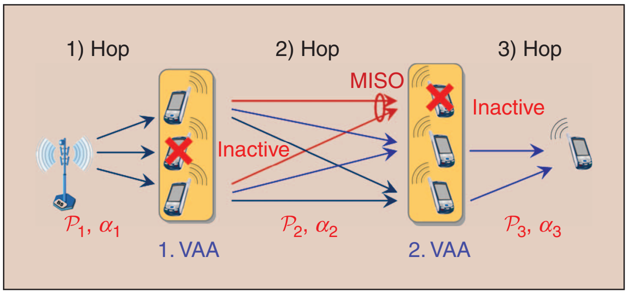

FIGURE 1 Topology of adaptive distributed MIMO multihop relay network.

At the first time fraction α_1, the source transmits data to the relays of the first VAA. The r_1 nodes of the first VAA decode the received signals separately to avoid enormous information exchanges, i.e., separate decoding is performed, which decomposes this hop to several single-input single-output (SISO) links (or multiple-input single-output (MISO) links at the next hops, as depicted in Figure 2). The τ_k relays that have successfully decoded the message (or being not in outage) are denoted as active nodes and the others that failed to decode the message (or being in outage) are denoted as inactive nodes, respectively. The inactive nodes will stop transmission at the next time fraction. The τ_k active nodes will adapt to transmit the decoded message cooperatively according to a space-time code with respect to τ_k antennas. To this end, each node transmits a spatial fraction of the space-time code word. If all relays within one VAA fail to decode the message, the e2e connection is considered to be in outage, denoted by the probability P_{e2e}. Otherwise, the τ_k active nodes send the data to the next VAA at the time fraction α_k. This adaptive transmission continues at each VAA until the message reaches the destination.

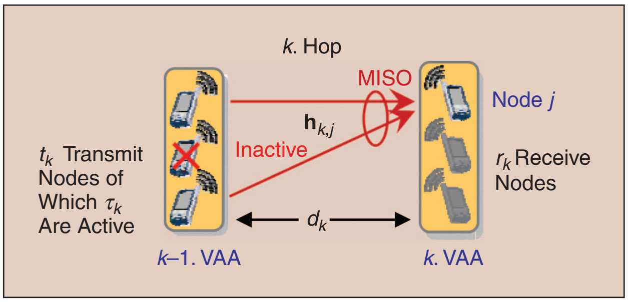

FIGURE 2 Hop k of the adaptive distributed MIMO multihop network with τ_k *active nodes*.

"AN ADAPTIVE MULTIHOP CONNECTION IS IN OUTAGE IF NO RELAY OF ONE HOP CAN DECODE THE MESSAGE CORRECTLY."

System Model

It is assumed that each relay transmits signals with the same data rate R. However, VAA k occupies the physical channel only for an individual time fraction α_k, of which the sum equals one. All the hops use the total bandwidth W that is available to the network. We define $\mathbf{S}_k$ as the space-time encoded signal from the τ_k active nodes at hop k. The received signal $\mathbf{y}_{k,j}$ at node j of VAA k corresponds to

$$\mathbf{y}_{k,j} = \sqrt{\frac{\mathcal{P}_k}{t_k\, d_k^{\varepsilon}}}\mathbf{h}_{k,j}\mathbf{S}_k + \mathbf{n}_{k,j}, \tag{1}$$

where $\mathbf{n}_{k,j}$ is the Gaussian noise vector with power spectral density N_0. Each active node of the VAA transmits data with power $\mathcal{P}_k/t_k$ equally. This permits simple power control and hardware implementation at each relay, which is especially important for relaying nodes with minimal processing functionality. Consequently, if some nodes in hop k are inactive (i.e., $\tau_k \le t_k$), the actual total transmit power of this hop is less than $\mathcal{P}_k$. The channel from the τ_k active nodes to the jth receive node within the kth hop is denoted as $\mathbf{h}_{k,j}$, whose elements obey the same uncorrelated Rayleigh fading statistics with unit variance. It is assumed that the relaying nodes belonging to the same VAA are spatially sufficiently close as to justify a common path loss between the two VAAs, which is known as *symmetric network*. The path loss is given by $d_k^{-\varepsilon}$, where d_k is the distance between two nodes and ε is the path loss exponent within the range of 2–5 for most wireless channels.

To meet a given quality-of-service (QoS) requirement, the transmit power $\mathcal{P}_k$ and the time fraction α_k per hop need to be optimized. In the next section, the e2e outage probability P_{e2e} is introduced as the QoS parameter. Based on this result, the optimization problem is subsequently presented.

e2e Outage Probability

Before formulating the outage probability $P_{\mathrm{out},k}$ of hop k, we first consider the outage probability $p_{\mathrm{out},k,j}(\tau_k)$ of a MISO system with τ_k active nodes at hop k, as described in (1) and shown in Figure 2. The instantaneous achievable rate of the link is given by

$$C_{k,j}(\tau_k) = \alpha_k W \log_2\left(1 + \frac{\mathcal{P}_k}{\alpha_k W t_k d_k^{\varepsilon} N_0}\left\|\mathbf{h}_{k,j}\right\|^2\right). \tag{2}$$

The outage probability $p_{\mathrm{out},k,j}(\tau_k)$ can be expressed as the probability that the channel cannot support an error-free transmission at data rate R, i.e.,

$$\begin{aligned} p_{\mathrm{out},k,j}(\tau_k) &= \Pr\{R > C_{k,j}(\tau_k)\}, \\ &= \Pr\left\{\left\|\mathbf{h}_{k,j}\right\|^2 < \left(2^{R/(\alpha_k W)} - 1\right)\frac{\alpha_k W t_k d_k^{\varepsilon} N_0}{\mathcal{P}_k}\right\}, \\ &= \Pr\left\{\left\|\mathbf{h}_{k,j}\right\|^2 < x_k\right\} = \frac{\gamma(\tau_k, x_k)}{\Gamma(\tau_k)}. \end{aligned} \tag{3}$$

To simplify the notation, the variable x_k being proportional to the inverse signal-to-noise-ratio (SNR) is used in (3). The squared energy of the channel, i.e., $\left\|\mathbf{h}_{k,j}\right\|^2$, is a random variable and obeys a Gamma distribution [14]. Therefore, its cumulative distribution function (CDF) is given by an incomplete Gamma function normalized by the Gamma function, as indicated in the last line of (3). Clearly, the outage probability $p_{\mathrm{out},k,j}(\tau_k)$ depends on the number of active nodes τ_k at hop k, whereas the probability of τ_k active nodes is determined by the outage probability of the nodes at the previous hop.

The outage probability of the receiving node j at hop k is denoted by $P_{\mathrm{out},k,j}$. Under the assumption of symmetric networks, the outage probabilities of the nodes within one VAA are equal, i.e., $P_{\mathrm{out},k,1} = P_{\mathrm{out},k,2} = \ldots = P_{\mathrm{out},k,r_k}$. The number of active nodes τ_k at hop k is a random number, which depends on the outage probabilities in the previous hop $k-1$. As these probabilities $P_{\mathrm{out},k-1,j}$ are equal, the number of active nodes τ_k follows the binomial distribution $\mathcal{B}$ with parameters t_k and $P_{\mathrm{out},k-1,j}$. The probability of τ_k nodes being active at hop k is expressed by the probability mass function as [14]

$$\Pr\{\tau_k\} = \binom{t_k}{\tau_k}\left(1 - P_{\mathrm{out},k-1,j}\right)^{\tau_k} P_{\mathrm{out},k-1,j}^{t_k-\tau_k}. \tag{4}$$

As the outage probability of a MISO system with τ_k active nodes is described by $\Pr\{\tau_k\}\cdot p_{\mathrm{out},k,j}(\tau_k)$, the outage probability $P_{\mathrm{out},k,j}$ equals the sum of the outage probabilities over all possible τ_k

$$P_{\mathrm{out},k,j} = \sum_{\tau_k=1}^{t_k}\Pr\{\tau_k\}\cdot p_{\mathrm{out},k,j}(\tau_k). \tag{5}$$

If all receive nodes of a hop cannot decode the message, the corresponding hop is in outage. Thus, the outage probability of hop k is given by

$$P_{\mathrm{out},k} = \prod_{j=1}^{r_k} P_{\mathrm{out},k,j} = P_{\mathrm{out},k,j}^{r_k}. \tag{6}$$

Consequently, the e2e connection is in outage if any hop is broken, and the e2e outage probability corresponds to

$$P_{\mathrm{e2e}} = 1 - \prod_{k=1}^{K}\left(1 - P_{\mathrm{out},k}\right) = 1 - \prod_{k=1}^{K}\left(1 - P_{\mathrm{out},k,j}^{r_k}\right). \tag{7}$$

In the following investigation, we use the e2e outage probability P_{e2e} as the measurement for the required QoS. For convenience, the different occurring probabilities are summarized in Table 1.

Optimum Joint Power and Time Allocation

The joint power and time allocation task for the adaptive relaying scheme is formulated in order to minimize the total power consumption meanwhile supporting a given e2e outage probability requirement e as follows

$$\begin{aligned} &\text{minimize} \quad \mathcal{P}_{\text{total}} = \sum_{k=1}^{K} \mathcal{P}_k (1 - P_{\text{out},k-1,j}) \\ &\text{subject to} \quad P_{\text{e2e}} \le e \ \text{ and } \ \sum_{k=1}^{K} \alpha_k = 1 \end{aligned} \tag{8}$$

The solution for the joint power and time allocation problem is referred to as JPTA. The calculation of $\mathcal{P}_{\text{total}}$ considers the inactive nodes stopping the transmission to save power. The problem of joint power and time allocation can be shown to be convex for low outage probability requirements by proving the Hessian matrix of P_{e2e} to be positive semi-definite. Thus, the optimal solution for the power allocation $\mathcal{P}_k^*$ and the time allocation α_k^* for the optimization problem can be obtained by standard optimization tools [15].

Based on an approximation for the capacity term (2) and some further estimations for the e2e outage probability P_{e2e} and the total power $\mathcal{P}_{\text{total}}$ a closed-form solution for the joint power and time allocation was derived in [13] using the Lagrangian of the approximated optimization problem. The evaluation of the Karush-Kuhn-Tucker conditions then leads to a low-complexity, but sub-optimal solution.

Optimum Power Allocation with Equal Time Assignment

In 12 the authors derived the optimum allocation problem for adaptive distributed MIMO multi-hop systems with only power allocation. Thus, the fraction of the total transmission time was equally assigned to each hop, i.e., $\alpha_k = 1/K$ and consequently (8) simplifies to

$$\begin{aligned} &\text{minimize} \quad \mathcal{P}_{\text{total}} = \sum_{k=1}^{K} \mathcal{P}_k (1 - P_{\text{out},k-1,j}) \\ &\text{subject to} \quad P_{\text{e2e}} \le e. \end{aligned} \tag{9}$$

The solution for the power allocation with equal time assignment problem is referred to as PA, and can again be calculated by standard optimization tools [13]. Furthermore, a closed-form near-optimum solution for (9) has been derived in [12] as well. As the power allocation problem has to be optimized only with respect to one variable, this closed-form solution requires less harmful approximations leading to a more robust solution than the closed form solution for JPTA.

The τ_K relays that have successfully decoded the message are denoted as active nodes and the others that failed to decode the message are denoted as inactive nodes, respectively.

Implementation Aspects

The described resource allocation schemes require the solution of the optimization task at a central position and the distribution of the time fractions and power allocations to the different nodes. However, as a pure statistical approach is chosen, no instantaneous knowledge as current channel realizations are necessary. Only if the geometry changes, i.e., the number of nodes per VAA or the hop distances, the resource allocation solution has to be adapted. However, for decreasing the computational complexity, the near-optimum closed-form solutions presented in [10]–[13] can be used.

Performance Evaluation

In the sequel, the performance of several resource allocation schemes are evaluated for two different multihop networks with $K = 3$ hops. It is assumed that the e2e communication over $W = 5$ MHz should meet an e2e outage probability constraint of $e = 1\%$, with the path loss exponent $\varepsilon = 3$ and noise power spectral density $N_0 = -174$ dBm/Hz. For comparison, the performance results are shown for a direct transmission from source to destination without the help of additional relays, nonadaptive transmission [9] with optimized power allocation, and adaptive transmissions with optimized resource allocations. Note that the solutions for resource allocations are always derived by means of standard optimization methods, although efficient and near-optimal closed-form solutions have been derived, e.g., [7]–[13].

System Configuration A

In this section, the multihop system shown in Figure 3 with three nodes per VAA and an equal distance between the nodes of $d = 1$ km is investigated.

TABLE 1 *Overview of probabilities occurring in the calculation of the e2e outage probability P_{e2e}.*

Variable	*Explanation*
$p_{\text{out},k,j}(\tau_k)$	Probability that receive node j of hop k is in outage if τ_k transmit nodes are active
$\Pr\{\tau_k\}$	Probability of τ_k active transmit nodes at hop k
$p_{\text{out},k,j}$	Probability that receive node j of hop k is in outage, considering all possible combinations of active transmit nodes
$P_{\text{out},k}$	Probability that hop k is in outage, i.e., no receive node of hop k was able to decode correctly
P_{e2e}	Probability that e2e connection is in outage

THE ADAPTIVE TRANSMISSION LEADS TO A MORE BALANCED DISPERSION OF THE POWER AND REQUIRES LESS POWER PER HOP IN COMPARISON TO NONADAPTIVE TRANSMISSION.

In Figure 4, the total power $\mathcal{P}_{\text{total}}$ versus the data rate R is shown for the different transmission and allocation schemes. In comparison to direct transmission from source to destination, the multihop systems achieve the same rate R with significant power reductions. For example, the nonadaptive multihop system results in a saving of approximately 18 dB. Further improvements are achieved by the adaptive transmission approaches, where only relays being not in outage participate at the transmission. It can be observed that the proposed adaptive transmission scheme with optimum resource allocation JPTA achieves a gain of approximately 12 dB in comparison to the nonadaptive scheme, where the e2e connection is in outage if any node in the network is in outage [9]. Interestingly, the adaptive transmission scheme with pure power optimization power allocation results in almost the same total transmit power.

Figure 5 depicts the power $\mathcal{P}_k$ assigned to the hops for the three multihop approaches under investigation. For the nonadaptive scheme, the first hop uses the most power, which is due to the lack of diversity degrees at this hop. Each relay of the VAA receives the signal only over one path, whereas transmit diversity can be exploited in

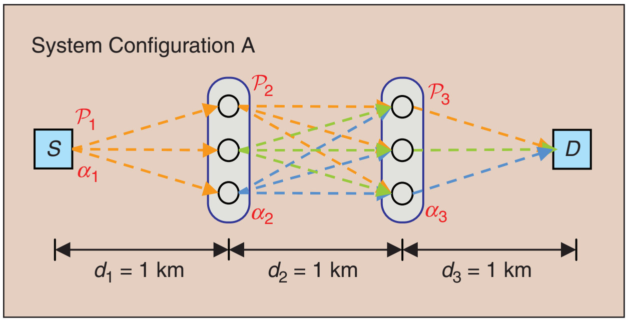

FIGURE 3 System configuration A with three nodes at both VAAs and equal distance of 1 km between hops.

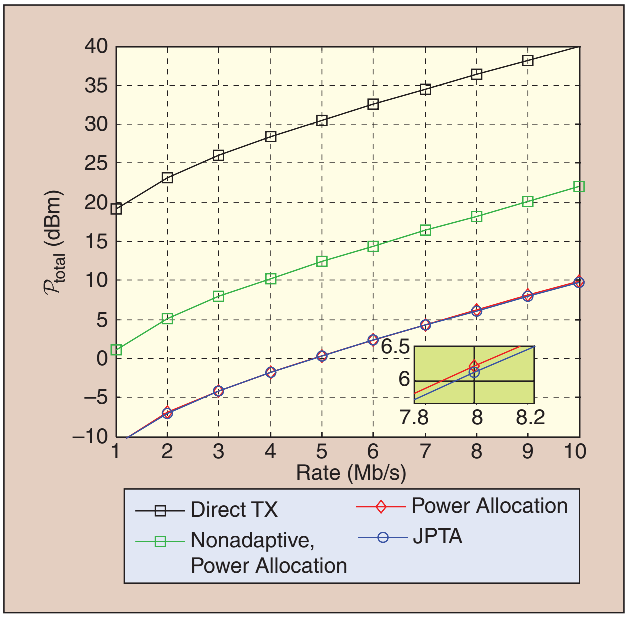

FIGURE 4 Total transmit power $\mathcal{P}_{\text{total}}$ (in dBm) for direct transmission, nonadaptive transmission with power allocation, and adaptive transmission with power allocation, and JPTA for system configuration A.

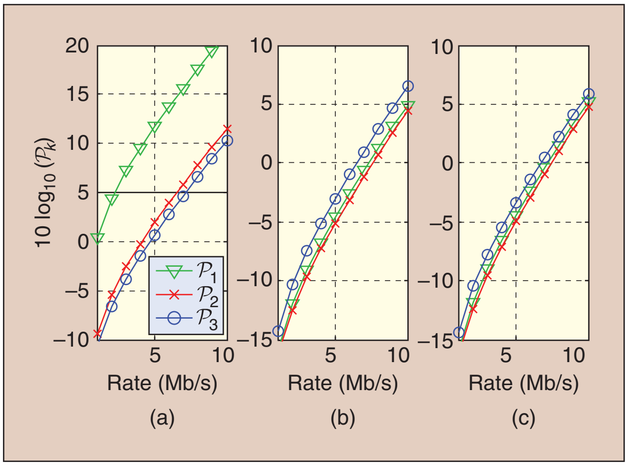

FIGURE 5 Power $\mathcal{P}_k$ per hop for (a) nonadaptive transmission and adaptive transmission with (b) power allocation, and (c) JPTA for system configuration A.

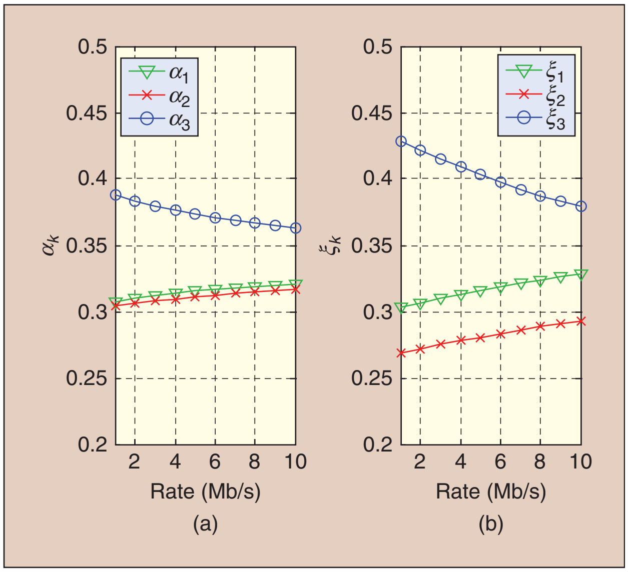

FIGURE 6 Optimum (a) time fraction α_k^* and (b) power fraction ξ_k per hop for JPTA for system configuration A.

the second and the third hop. In contrast, the adaptive schemes consume most energy in the last hop. The reason for this is that there is only one node at the destination which has to decode the data correctly, otherwise an outage event occurs. Similarly, at the source, there are no nodes to transmit the data cooperatively with high diversity degrees. Thus, the source consumes the second most power. Because of the adaptive scheme and space-time coding at the second hop, this hop uses the least power. Comparing the adaptive schemes, the equivalence of power allocation and JPTA becomes obvious. Both consume approximately the same power per hop to meet the e2e outage requirement P_{e2e}. In general, the adaptive transmission leads to a more balanced dispersion of the power and requires less power per hop in comparison to nonadaptive transmission.

To justify the equivalence of power allocation and JPTA for this system configuration, the behavior of the optimum time fraction α_k^* per hop determined by JPTA is depicted in Figure 6(a). For this system configuration, almost equal time is spent for each hop, which corresponds to the assumed time allocation $\alpha_k = 1/3$ for power allocation. Consequently, both allocation approaches result in roughly the same total transmit power. In Figure 6(b), the fraction of total power assigned to the hops, i.e., $\xi_k = \mathcal{P}_k^*/\mathcal{P}_{\text{total}}^*$, is illustrated. The discussed property that the last hop requires the most power to ensure correct detection at the receiver is clarified. In addition, by comparing both subplots, a similar behavior for α_k^* and ξ_k can be observed.

System Configuration B

For the second considered scenario, it is assumed that the first and second VAA contain two and five nodes, respectively. The system is depicted in Figure 7, where it is assumed that the distance between the VAAs are $d_1 = 3$ km and $d_2 = d_3 = 1$ km. Obviously, the link between the source and the first VAA is the weakest and will correspondingly require most of the resources.

The total transmit power for the different allocation schemes is shown in Figure 8. The adaptive transmission scheme with pure power optimization power allocation results already in strong power reductions compared with nonadaptive transmission. However, the loss of approximately 2 dB with respect to JPTA affirms the necessity to allocate both resources power and time jointly in this scenario.

The corresponding assignment of transmit power to the different hops is illustrated in Figure 9. Because of the large distance between the source and the first VAA, the adaptive schemes allocate most of the power to the source currently.

Finally, Figure 10 shows the fraction of time and the relative power per hop for this system configuration. The figure clarifies that most resources (time and power) are assigned to the weakest link. Specifically, the time per hop

A JOINT OPTIMIZATION OF POWER AND TIME (OR BANDWIDTH) IS FAVORABLE FOR SYSTEMS WITH NONEQUAL LINK STRENGTH.

is no longer equal but differs significantly for the optimum solution JPTA. Correspondingly, the solution power allocation (with $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$) leads to an increased total transmit power as observed in Figure 8. Thus, for multihop systems with strongly differing links, the joint allocation of power and time should be considered.

Summary

In this article, an adaptive distributed MIMO multihop network was presented, and the e2e outage probability was

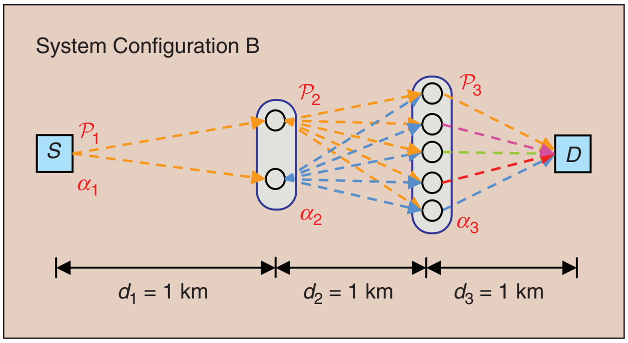

FIGURE 7 System configuration B with two nodes at the first and five nodes at the second VAA and distances of $d_1 = 3$ km, $d_2 = d_3 = 1$ km between the hops.

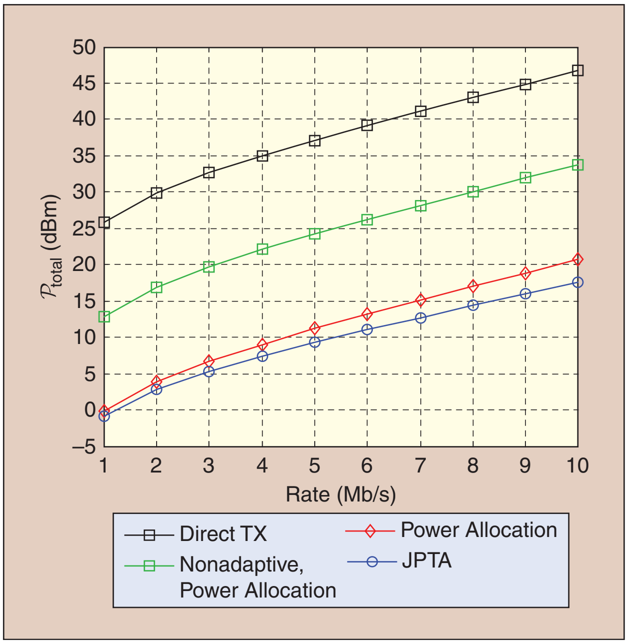

FIGURE 8 Total transmit power $\mathcal{P}_{\text{total}}$ (in dBm) for direct transmission, nonadaptive transmission with power allocation and adaptive transmission with power allocation, and JPTA for system configuration B.

THE ADAPTIVE MULTIHOP SCHEME OUTPERFORMS THE DIRECT TRANSMISSION AND THE NONADAPTIVE MULTIHOP SCHEME SIGNIFICANTLY.

derived as the QoS parameter. The task of assigning the physical resources transmit power and the time to reduce the total transmit power while meeting a given QoS constraint was introduced and solved by means of common convex optimization tools. As shown by numerical investigations, the adaptive multihop scheme outperforms the direct transmission and the nonadaptive multihop scheme significantly. Furthermore, a joint optimization of power and time (or bandwidth) is favorable for systems with nonequal link strength.

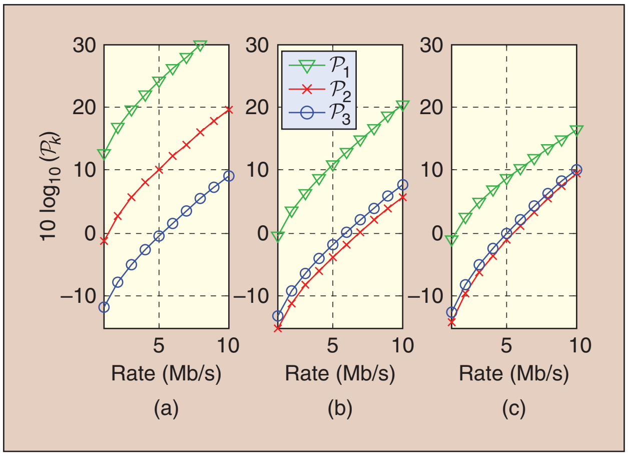

FIGURE 9 Power $\mathcal{P}_k$ per hop for (a) nonadaptive transmission and adaptive transmission with (b) power allocation, and (c) JPTA for system configuration B.

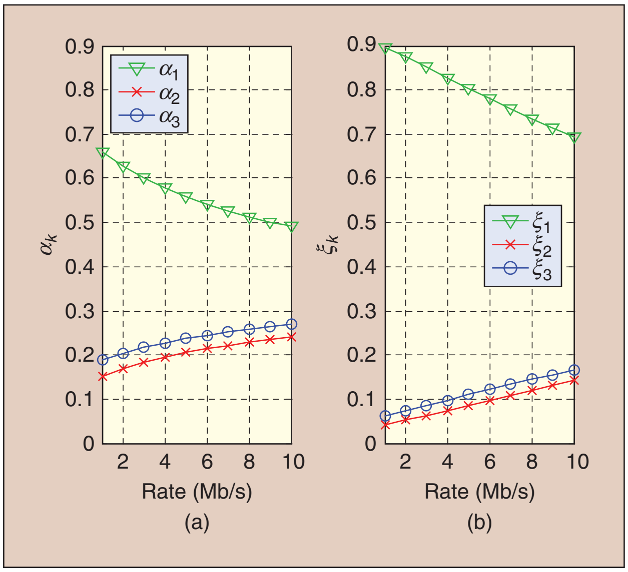

FIGURE 10 Optimum (a) time fraction α_k^* and (b) power fraction ξ_k per hop for JPTA for system configuration B.

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