A Distributed Relay Beamforming-enhanced TDMA System

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***Abstract*—Token-passing wireless network protocols (TP-WNP) (e.g., EchoRing), designed for hard real-time systems, typically need to provide ultra-low-latency coupled with ultra-high-reliability guarantees. In this paper, we initiate a study to investigate the feasibility of distributed relay beamforming (DRBF) in a TP-WNP with the aim to enhance its reliability (and latency) performance even further. Specifically, we consider employing N i) amplify-and-forward (AF), ii) decode-and-forward (DF) relays in a wireless network running a TP-WNP. The relays operate in FDD mode, and do distributed transmit beamforming to realize low-latency, highly-reliable communication between each of the M source-destination pairs in the TP-WNP (a.k.a TDMA) system.**

The enablers/pre-requisites for the proposed DRBF-TDMA system are frequency, phase and timing synchronization among the relay nodes. To this end, we propose a novel distributed method for frequency synchronization among the AF/DF relay nodes operating in FDD mode. Furthermore, for oscillators with drift, we derive a rule of thumb which provides us the maximum relaying delay T_{delay} up to which the proposed frequency synchronization method is effective. For phase and timing synchronization, we employ standard techniques from the literature. Our simulation results verify the analytical results, i.e., by means of proposed DRBF using N AF (DF) relays, upto a factor of N (N^2) gains in received SNR can be achieved, at each of the M destination nodes in the proposed system.

I. Introduction

A hard real-time (HRT) system is mainly characterized by small packet sizes/low data rates along with stringent requirements of ultra-high reliability (>1-1E-5) and ultra-low latency (~10 ms). An example application of HRT systems is industrial automation where they have been traditionally realized by *wired* fieldbus protocols operating on token-passing principle, e.g., ProfiBus [1] etc. More recently, there has been a growing interest in realizing *wireless* network protocols with their design tailored for the requirements and specifications of HRT systems. These wireless network protocols then inherit the token-passing principle from their wired counterparts (ProfiBus) to implement a distributed TDMA system, e.g., EchoRing [2] etc.

A token-passing wireless network protocol (TP-WNP), a.k.a distributed TDMA system, helps up to some extent to realize bounded latency, but wireless networks, due to dynamic nature of propagation medium (i.e., fading), are inherently unreliable. But since reliability and latency are tightly-coupled parameters, one needs to have high-reliability (i.e., lesser re-transmissions) to ensure low-latency. Indeed, this is the approach adopted by EchoRing [2] where cooperative relaying is employed to enhance the reliability of overall system, which in turn helps in realizing a bounded low-latency.

With the low-latency and high-reliability challenges of HRT systems in mind, we initiate a study to investigate the feasibility of distributed relay beamforming (DRBF) in a TP-WNP (e.g., EchoRing). Being more specific, in this preliminary work, we are mainly interested to investigate the (receive) power gains provided by DRBF in a distributed TDMA system setting. The broader objective of this work, however, is to propose DRBF as a candidate solution for integration into the EchoRing and other TP-WNP's designed for HRT systems.

Contributions.

1) We present DRBF-TDMA, a novel architecture, first of its kind, targeted at HRT systems. We propose employing N amplify-and-forward (AF), or, decode-and-forward (DF) relays which operate in FDD mode, and do distributed transmit beamforming to realize low-latency, highly-reliable communication between each of the M source-destination pairs in a TDMA system. We then identify challenges (mainly frequency, phase and timing synchronization among relay nodes), provide viable solutions (a novel frame structure, a novel frequency synchronization scheme etc.) and highlight (receive) SNR gains, for the proposed DRBF-TDMA architecture.
2) We propose a novel distributed method for frequency synchronization among the AF/DF relay nodes operating in FDD mode. Then, for drifting oscillators, we provide a simple analytical expression for maximum relaying delay T_{delay} in terms of system and clock parameters.
3) Our simulation results verify the analytical results, i.e., by means of proposed DRBF using N AF (DF) relays, upto a factor of N (N^2) gains in received SNR can be achieved, at each of the M destination nodes in the system.

At this point, it is worth mentioning that the proposed DRBF-TDMA architecture is equally well-suited for any other TP-WNP (or, any centralized/distributed TDMA system, in general). For example, one could investigate DRBF for WirelessHART, Bluetooth low energy, IEEE 802.11ah, WTRP [3].

Outline. The rest of this paper is organized as follows. Section II summarizes selected related work. Section III discusses the system architecture for the proposed DRBF-TDMA system. Section IV describes the proposed distributed method for frequency synchronization among the AF/DF relay nodes operating in FDD mode. Section V provides simulation results. Finally, Section VI concludes the paper.

II. Related Work

Though there has been lots of interest in cooperative relaying as well as centralized/distributed beamforming, only a few works have considered the two problems jointly. In [4], [5], authors design a system where an AF relay cluster (consisting of N single-antenna nodes) receives data from a distant node and forwards it via distributed transmit beamforming to a processing center in order to achieve over-the-air distributed receive beamforming at the processing center. [6] considers opportunistic collaborative beamforming where a designated receiver node sends a single bit of feedback to each relay in order to dictate whether or not it should participate in beamforming process. [7] investigates the problem of network beamforming and optimal power control under the condition that the relays have perfect channel state information. In [8], authors derive a distributed method to compute the approximately SINR-optimal beamforming weights at relay nodes when multiple interferers transmit simultaneously along with the actual source node. Zheng et. al. design distributed methods for collaborative relay beamforming when the sender can acquire perfect channel state information (CSI) [9], and imperfect CSI [10], for the channels between relay nodes and the destination. [11] designed and implemented a three-node DSTBC system (one source-destination pair plus a relay) on WARP software-defined radios while addressing the problem of frequency synchronization between source and relay node, for the two relaying strategies, i.e. AF and DF. Finally, [2] exploits cooperative relaying to enhance the reliability performance of EchoRing. Nevertheless, to the best of authors' knowledge, the problem of distributed relay beamforming for a TDMA system has not been considered before.

III. Proposed DRBF-TDMA system

A. System Architecture

Consider a wireless network consisting of M single-antenna nodes running a TP-WNP (e.g., EchoRing). A TP-WNP is basically a distributed TDMA system which works as follows. All the M nodes form a *logical* ring $\mathcal{R}$ where every node knows its predecessor and successor. Then, a small packet (of duration T_{token}) called *token* is rotated between the nodes in the ring. The token dictates the right for transmission; i.e., only the node which currently holds the token is allowed to transmit (for duration T_p) after which it must yield the token to its successor.

Now, in our system model, each source node S_m, during its transmission turn (a.k.a THT[1]), talks to a destination node D_m *within* the ring, i.e., $\{S_m, D_m\}^2 \in \mathcal{R} \ \forall \ m = 1, ..., M$. Finally, for every S_m, $\{S_m, D_m\}$ remains the same across the TRT's[3]. In other words, all the M source-destination pairs are time invariant, i.e., they don't change across TRT's.

Next, with the aim of enhancing the reliability (and hence the latency) performance of the TP-WNP at hand, we introduce an additional, dedicated set of N single-antenna relay nodes in the system. The relay cluster/compound relay (denoted as R) then operates in FDD/full-duplex mode. That is, during every THT, R overhears the transmission within the actual ring (without being part of the ring), on a frequency f_{SR}. Then, during next THT, it re-transmits/forwards the overheard noisy (clean) packet using AF (DF) strategy, via *distributed beamforming*, on a different frequency f_{RD} (see Fig. 1).

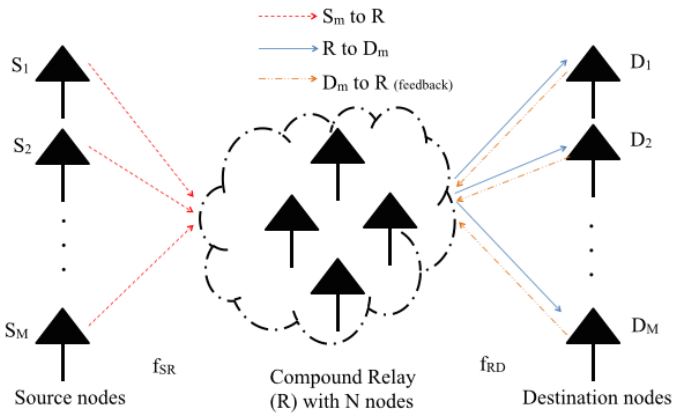

Fig. 1. Proposed DRBF-TDMA system architecture.

The FDD mode of operation of R implies that the receive nodes within the actual ring also operate in FDD mode. That is, a destination node, during its first THT-long reception interval, listens on frequency f_{SR}; and then during the second THT-long reception interval, listens on frequency f_{RD}. This means if a destination node does not receive a packet during the first THT interval, then distributed beamforming by R during next THT interval makes it very unlikely that the destination will drop the packet again. Thus, DRBF greatly helps to reduce packet error rates, increase reliability (and hence decrease the latency) of the underlying TP-WNP.

Conceptually, we now have two logical rings in the system; an *actual* ring (of size M) where nodes take turn to transmit their data, and a *helper* ring (of size 1) where R take turns to echo the overheard transmissions to different receive nodes[4] (see Fig. 2). Note also from Fig. 2 that the time-gap between a transmission by actual ring and its echo from helper ring is 1 THT[5].

[1]THT=token holding time; THT=$T_p + T_{token}$.

[2]Note that $D_m \neq S_m$. Rather $D_m = S_j \ \forall \ j = 1, ..., M$ and $j \neq m$.

[3]TRT=token rotation time; i.e., time interval after which a node S_m gets the token again. $TRT = M \times THT$.

[4]Note that, in our system model, R works in a proactive rather than reactive manner. That is, no matter whether a transmission succeeded or failed in previous THT, it always forwards the overheard data to its destination.

[5]This is based on the assumption that helper (slave) ring is implicitly time synchronized to actual (master) ring by only passive listening to periodic token transmissions by master ring. We will make use of this assumption throughout the rest of the paper.

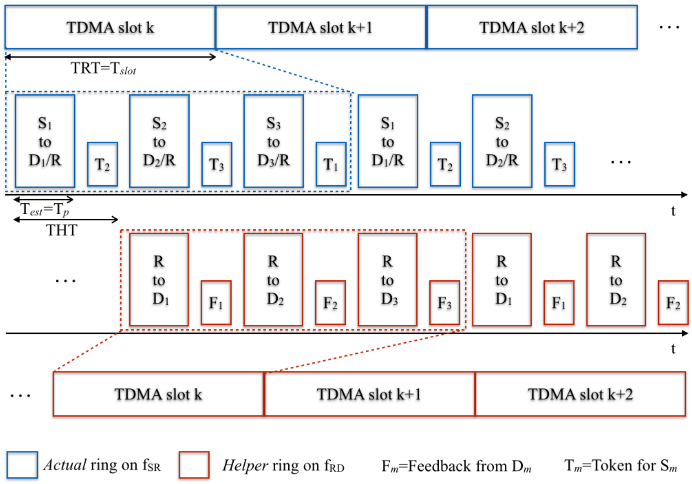

Fig. 2. Events timeline (frame structure) for proposed DRBF-TDMA system (M = 3).

Realizing DRBF via an additional logical ring on a different frequency has several advantages, such as: i) modular system architecture (which means proposed DRBF scheme can be incorporated into existing TP-WNP's as merely an additional layer, rather than re-designing the system from scratch), ii) frequency diversity etc.

B. Distributed Relay Beamforming

As is briefly mentioned before, it is solely the distributed relay beamforming which acts as a springboard to realize the highly-reliable DRBF-TDMA system in Fig. 1. To better highlight the gains and challenges of distributed relay beamforming as well as to offer viable solutions, we turn our attention to a simplified system model (see Fig. 3) for the rest of this section and section IV. With this, a related objective is to complement the work in [4] which considers a cluster of AF relays operating in half-duplex/TDD mode for distributed *receive* beamforming, and discusses the gains and challenges followed by potential solutions.

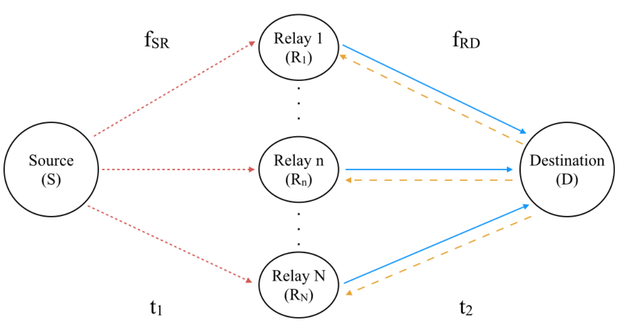

Fig. 3. DRBF-TDMA system with M = 1.

Gains due to distributed relay beamforming. With N DF relays, received SNR gains upto a factor of N^2 can be achieved at the destination D[6] (see Appendix A). On the other hand, with N AF relays, received SNR gains upto a factor of N can be achieved at the destination D [4].

Challenges of distributed relay beamforming. Distributed (AF/DF) relay beamforming requires precise frequency, phase and timing synchronization among all the N cooperating relay nodes [4].

Solutions. In Section IV, we present a novel distributed method for frequency synchronization among the cooperating (AF/DF) relay nodes operating in FDD mode. For phase synchronization, we have made use of a distributed, stochastic-search based, iterative algorithm[7] from [12] (so-called 1-bit feedback algorithm) which has been proved analytically to converge to the global optimum. Finally, for timing synchronization, the cooperating (AF/DF) relays could exploit the time-of-packet-arrival (ToPA) of received packets on the first hop to later use it as a common trigger event for their packets' transmission on second hop; this assumption works well for narrow-band system setting we have assumed in this work. In other words, each of the N relay nodes, when receiving a packet from source S, computes ToPA t_{ToPA}; adds to it a common pre-specified delay T_{delay}, and sends its packet towards the destination D at its local time $t_{ToPA} + T_{delay}$.

IV. Frequency Synchronization Among AF/DF Relay Nodes in FDD Mode

With the simplified system model of Fig. 3 in mind, we now turn our attention to the problem of frequency synchronization among AF/DF relay nodes operating in FDD mode. However, we deem it important to summarize first a recent result from literature [4] which addresses the problem of frequency synchronization among AF relay nodes operating in TDD mode.

A. When AF relays operate in TDD mode

Remark IV.I [4]. When *AF* relay nodes operate in TDD/half-duplex mode, no explicit mechanism for frequency synchronization among relay nodes is needed[8] (for the purpose of distributed relay beamforming at the destination node D), provided that following condition is met:

$$T_{delay} \leq \left(\frac{3ln\frac{1}{\alpha}}{(2\pi f_c)^2 q_2^2} \right)^{1/3} \quad (1)$$

where T_{delay} is the relaying delay, i.e., the time gap between the instant t_1 when a packet is transmitted by the source node S and the instant t_2 when it is forwarded by compound relay

[6] provided that the frequency correction mechanism at relay nodes is sufficiently accurate.

[7] Any phase synchronization algorithm will require few bits of feedback from D_m to R every TRT so that R can periodically update its beam orientation towards D_m, e.g., [12], [13], [14]. In our system model, D_m sends a feedback packet to R immediately after it receives a relayed packet from R (see Figs. 1, 2).

[8] However, when *DF* relay nodes operate in TDD/half-duplex mode, then an explicit mechanism for frequency synchronization among relay nodes is needed. In fact, in this case, one can simply apply the frequency synchronization method proposed in section IV-B1 and use the design rule given in section IV-B2 by setting β = 1 in Equations (10) and (12) respectively.

node R to destination node D. α is the desired level of received beamforming power as a fraction of normalized theoretical maximum; $0 \le \alpha \le 1$. q_2^2 is a clock-model parameter which represents random walk frequency noise [15]. Finally, f_c is the center frequency (in Hz) of the wireless channel, i.e. when AF relay nodes operate in TDD/half-duplex mode, $f_c = f_{SR} = f_{RD}$.

Justification [4]. Let $\Delta f_{S,R_n}(t_1)$, $\Delta f_{R_n,D}(t_1)$, $\Delta f_{S,D}(t_1)$ represent the frequency offset at time t_1, when source S transmits to relay R_n, relay R_n transmits to destination D, source S transmits to destination D respectively. Then, for oscillators with no drift, the following relationship holds:

$$\Delta f_{S,R_n}(t_1) + \Delta f_{R_n,D}(t_1) = \Delta f_{S,D}(t_1), \forall n = 1, ..., N \quad (2)$$

In other words, the relay offsets on the two hops cancel each other out in Equation (2), and therefore, explicit frequency synchronization among relay nodes is not required.

However, in case of oscillators with significant drift, equation (2) does not hold for large $T_{delay} = t_2 - t_1$ values. Then, for a desired power level α, (1) provides an upper-bound on relaying delay T_{delay} up to which the explicit frequency synchronization among relay nodes is not required.

B. When AF/DF relays operate in FDD mode

Remark IV.II. When AF/DF relay nodes operate in FDD/full-duplex mode, an explicit mechanism for frequency synchronization among relay nodes is needed (for the purpose of distributed relay beamforming at the destination node D).

Justification. In FDD/full-duplex mode, $f_{SR} \ne f_{RD}$. In other words, during first time-slot starting at time t_1, relay node R_n receives data from source node S on a channel with center frequency f_{SR}; and then during second time-slot starting at time t_2, the relay node R_n forwards the data towards destination D on another channel with center frequency f_{RD}. Without loss of generality, let us assume that $f_{SR} < f_{RD}$. Let $\beta = \frac{f_{SR}}{f_{RD}}$. Then, $0 < \beta < 1$. Then, the following relationship holds:

$$\Delta f_{S,R_n}(t_1, f_{SR}) = \beta \Delta f_{S,R_n}(t_1, f_{RD}), \forall n = 1, ..., N \quad (3)$$

That is, for every node pair, the two frequency offsets at two different channel frequencies are scaled multiple of each other. Then, for oscillators with no drift, the relationship in (4) holds[9].

Hence, when AF/DF relay nodes operate in FDD/full-duplex mode, the net frequency offset at destination node is different for different relays which calls for some explicit means of frequency synchronization among the relay nodes; otherwise, distributed relay beamforming will suffer from fading loss. Below, we present one such method.

1) Proposed Method for Frequency Synchronization: The proposed method consists of two steps: each relay individually does i) frequency offset estimation, ii) frequency correction, in order for all the N relays to each frequency synchronization at the destination node.

[9]Note that (2) makes a special case of (4), i.e., (2) can be obtained from (4) by setting $\beta = 1$.

Frequency Offset Estimation. We assume a narrowband system where all the nodes exchange unmodulated sinusoids to each other. During training interval $t \in [0, T_{est}]$, source node S transmits its baseband signal $x(t)$ to all relay nodes on the channel with center frequency f_{SR}. Then, relay R_n receives a baseband signal:

$$y_n(t) = A_n x(t) e^{j(2\pi \Delta f_{S,R_n} t + \phi_{S,R_n})} + v_n(t) \quad (5)$$

where A_n is the received signal amplitude and $v_n(t)$ is the AWGN at R_n. Assuming $A_n = A$ and $i.i.d$ noise for all relay nodes, we have $\gamma_1 = \frac{A^2 T_{est}}{2N_0}$ where γ_1 is the common first-hop SNR, i.e., γ_1 is assumed to be the same for all the (S, R_n) links; N_0 is the power spectral density of $v_n(t)$. When $x(t) = 1$, then R_n is able to obtain one-shot phase offset estimate, $\hat{\phi}^{(1)}_{S,R_n} \sim N(\phi_{S,R_n}, \sigma^2_\phi)$ with $\sigma^2_\phi = \frac{2}{\gamma_1}$; and one-shot frequency offset estimate, $\widehat{\Delta f}^{(1)}_{S,R_n} \sim N(\widehat{\Delta f}_{S,R_n}, \sigma^2_f)$ with $\sigma^2_f = \frac{3}{2\pi^2 T^2_{est} \gamma_1}$ [16], [17]. However, as can be easily seen, the one-shot frequency estimate $\widehat{\Delta f}^{(1)}_{S,R_n}$ of [16], [17] has a T_{est}-dependent variance which makes it quite unreliable for short training interval T_{est} values. More precisely, in order to realize distributed relay beamforming for the system in Fig. 3 using $\widehat{\Delta f}^{(1)}_{S,R_n}$, i) very long T_{est}, ii) very high γ_1 and iii) almost instantaneous relaying by R_n are needed[10].

Therefore, we resort to the following two-shot frequency offset estimate [18]:

$$\widehat{\Delta f}^{(2)}_{S,R_n} \doteq \frac{\hat{\phi}^{(1)}_{S,R_n}(T_{slot}) - \hat{\phi}^{(1)}_{S,R_n}(0)}{2\pi T_{slot}} \quad (6)$$

where T_{slot} is the time gap between two successive T_{est}-seconds long packets from source S. Remember, $T_{est} < T_{delay} < T_{slot}$.

Then, assuming short training intervals, i.e. $T_{est} \Delta f_{S,R_n} \ll 1$, Equation (5) can be approximated as:

$$y_n(t) \approx A e^{j(\phi_{S,R_n})} + v_n(t) \quad (7)$$

We can then use the following simple one-shot ML phase offset estimate [19]:

$$\hat{\phi}^{(1)}_{S,R_n} \doteq \angle \left(\int_0^{T_{est}} y_n(t) dt \right) \quad (8)$$

Frequency Correction. Having obtained $\widehat{\Delta f}^{(2)}_{S,R_n}$ and $\hat{\phi}^{(1)}_{S,R_n}$, relay R_n proceeds as follows. In case of AF relaying, R_n frequency scales its (noisy) received signal $y_n(t)$ to generate a new signal $z_{n,AF}(t)$ as follows:

$$z_{n,AF}(t) = y_n(t) e^{j(2\pi \widehat{\Delta f}^{(2)}_{S,R_n} (\frac{1-\beta}{\beta}) t)} \quad (9)$$

On the other hand, in case of DF relaying, R_n frequency scales its (perfectly) reconstructed signal $x(t)$ to generate the new signal $z_{n,DF}(t)$ as follows:

$$z_{n,DF}(t) = x(t) e^{j(2\pi \widehat{\Delta f}^{(2)}_{S,R_n} (\frac{1}{\beta}) t + \hat{\phi}^{(1)}_{S,R_n})} \quad (10)$$

[10]The proof of this claim is omitted due to lack of space.

$$\Delta f_{S,R_n}(t_1, f_{SR}) + \Delta f_{R_n,D}(t_1, f_{RD}) = \beta \Delta f_{S,R_n}(t_1, f_{RD}) + \Delta f_{R_n,D}(t_1, f_{RD}) \neq \Delta f_{S,D}(t_1, f_{RD}), \forall n = 1, ..., N \quad (4)$$

Relay R_n then applies, to frequency corrected signal $z_{n,AF}(t)$ ($z_{n,DF}(t)$), a random phase shift according to algorithms in [13], [14] and a delay (for the purpose of distributed beamforming at the destination), amplifies the net signal and finally dispatches it.

This way, for oscillators with no drift, the relationship in (11) holds. Equation (11) implies that, by means of proposed method, the relay offsets on the two hops cancel each other out, and therefore, frequency synchronization among relay nodes is achieved at destination node.

The proposed method for frequency synchronization is a distributed method since all the relay nodes will be running this method independent of each other. Moreover, from the perspective of general system model in Fig. 1, it is a blind method. That is, the relay nodes will be running this method while being oblivious to which source is transmitting.

2) Rule of Thumb for T_{delay}: For oscillators with drift, one is interested to find the maximum relaying delay T_{delay} up to which the proposed frequency synchronization method is effective. In our system model, AF/DF relays operate in FDD mode, therefore, measurement noise is also present in addition to process noise. Hence, (1) cannot be used as is. Then, we have the new rule of thumb:

$$T_{delay} \leq \left(\frac{3\beta^2 [ln(\frac{1}{\alpha}) - \frac{4}{\beta^2 M^2 \gamma_1}]^+}{(2\pi f_c)^2 q_2^2} \right)^{1/3} \quad (12)$$

where $[.]^+ := max(0, [.])$, M is number of source-destination pairs (see Fig. 1). The derivation of (12) has been provided in Appendix B.

V. SIMULATION RESULTS

Simulation Methodology. We modeled the clock evolution (i.e., phase and frequency evolution) of each of the M source-destination pairs and N relays (w.r.t an ideal clock) as brownian motion [15]. We then assumed perfect timing synchronization among the relay nodes. Then, we implemented the proposed frequency synchronization algorithm from section IV-B1 at the relays. Finally, we implemented the 1-bit feedback phase control algorithm from [12] at relays, to realize the received power gains due to DRBF at destination nodes.

Simulation parameters. We set $M = 5$, $N = 10$, $TRT = T_{slot} = 5$ msec, $THT = 1$ msec, $T_p = 0.8$ msec. Furthermore, we used a system sampling rate of 20 Ksps. Then, to model the clocks of all the nodes, we used $q_1^2 = 8.47 \times 10^{-22}$, $q_2^2 = 5.51 \times 10^{-18}$, and frequency stability of ± 0.1 ppm. We then set the packet rate to 200 packets/sec per source node. We used a receive SNR of γ_1 =30 dB to compute the phase estimate in (8). Finally, we set f_{SR} = 900 MHz, and f_{RD} = 930 MHz.

A. Results

To demonstrate the effectiveness of proposed frequency synchronization method, Fig. 4 plots one realization of actual frequency offset $\Delta f_{S,R_1}$ along with its two-shot frequency offset estimate $\widehat{\Delta f}^{(2)}_{S,R_1}$ over time when R_1 does phase and frequency offset estimation using (8), (6).

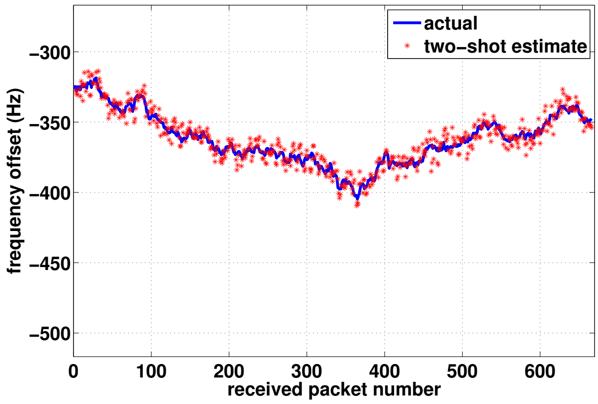

Fig. 4. Two-shot frequency offset estimation at relay R_1.

Next, Fig. 5 shows the received power gains, due to DF-DRBF with N relays, at each of the M destination nodes in the system. Note that, near-ideal power gains (close to 20 dB, the theroetical maximum) at all the M destination nodes are achieved.

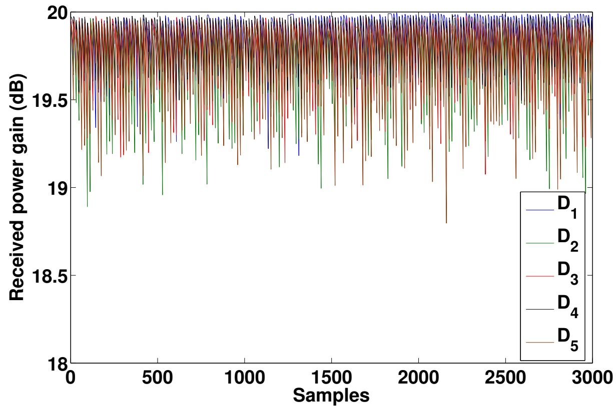

Fig. 5. Received power gains due to DF-DRBF.

Fig. 6 then provides the zoomed-in view of Fig. 5. That is, it shows the received power gains due to DF-DRBF at all the M destinations during 1 TRT. Equivalently, Fig. 6 shows the received SNR (as a function of time) observed at a destination as it receives a packet from the relays. Essentially, Fig. 6 highlights the decrease in receive SNR over time at a given destination, due to gradual lack of phase coherence among the relays due to drift of their individual clocks over time.

$$\frac{1}{\beta}\Delta f_{S,R_n}(t_1, f_{SR}) + \Delta f_{R_n,D}(t_1, f_{RD}) = \Delta f_{S,R_n}(t_1, f_{RD}) + \Delta f_{R_n,D}(t_1, f_{RD}) = \Delta f_{S,D}(t_1, f_{RD}), \forall n = 1, ..., N \quad (11)$$

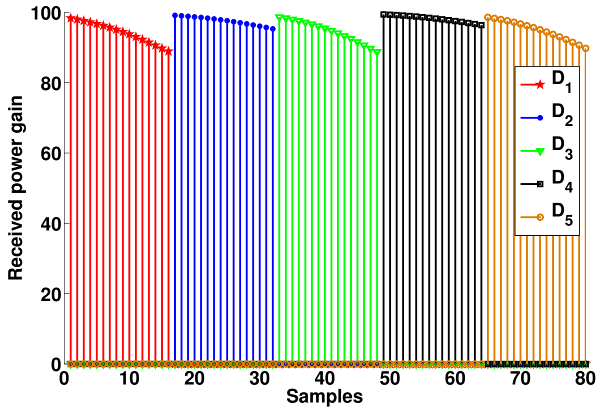

Fig. 6. Received power gains due to DF-DRBF during 1 TRT.

Fig. 7 shows the received power gains, due to AF-DRBF with N relays, at each of the M destination nodes in the considered system. Again, near-ideal power gains (close to 10 dB, the theroetical maximum) at all the M destination nodes are achieved.

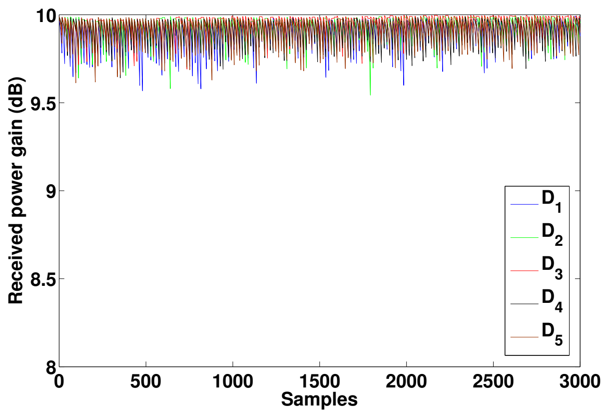

Fig. 7. Received power gains due to AF-DRBF.

VI. Conclusion

In this paper, we investigated the feasibility of DRBF in a TP-WNP with the aim to enhance its reliability (and latency) performance even further. Specifically, we considered N i) AF, ii) DF relays, operating in FDD mode, in a wireless network running TP-WNP. The relays performed distributed transmit beamforming to realize low-latency, highly-reliable communication between each of the M source-destination pairs in the underlying TP-WNP.

To realize proposed DRBF-TDMA system, we proposed a novel distributed method for frequency synchronization among the AF/DF relay nodes operating in FDD mode. Then, for oscillators with drift, we derived a rule of thumb to provide us the maximum relaying delay T_{delay} up to which the proposed frequency synchronization method is effective. For phase and timing synchronization, we employed standard techniques from the literature. Our simulation results verified the analytical results, i.e., by means of proposed DRBF using N AF (DF) relays, upto a factor of N (N^2) gains in received SNR can be achieved, at each of the M destination nodes in the DRBF-TDMA system.

Future work will include employing Kalman filtering at relays to obtain better frequency offset estimates (due to its SNR improvement property). We will also look into the issue of systematic design of DRBF-TDMA system parameters.

Appendix A
SNR gain due to distributed DF relay beamforming

For below analysis, we assume that relay nodes are already frequency synchronized by means of proposed method in Section IV-B1. We assume that, at time k, source transmits data symbol $p[k]$ with normalized power constraint $E|p[k]|^2 = 1$. Then, the received symbol $q[k]$ at relay R_n is $q[k] = h_{S,R_n} \times p[k] + n_n[k]$ where h_{S,R_n} is the channel between source and relay R_n, and $n_n[k]$ is the noise at the relay R_n. The relay R_n decodes the message to retrieve the symbol $x[k]$, applies phase shift $\theta_n[k]$ for beamforming and gain a_n against fading, and then forwards the message to the destination. Then, at the destination, assuming perfect timing alignment, the sum received signal is:

$$r[k] = \sum_{n=1}^{N} (h_{R_n,D} \times A_n[k] \times x[k]) + n_D[k] \quad (13)$$

where $A_n[k] = a_n e^{j\theta_n[k]}$, $h_{R_n,D}$ is the channel between relay R_n and destination, and $n_D[k]$ is the noise at the destination. Then, the SNR at destination due to distributed relay beamforming is:

$$\gamma_{D,R} = \frac{E[|\sum_{n=1}^{N} h_{R_n,D} \times A_n[k] \times x[k]|^2]}{E|n_D[k]|^2} \quad (14)$$

Assuming perfect coherence and that the noise has the variance N_0, we have the following expression:

$$\gamma_{D,R} = \frac{E[(\sum_{n=1}^{N} |h_{R_n,D}| \times |A_n[k]| \times |x[k]|)^2]}{N_0} \quad (15)$$

Let us assume that all the relay nodes have equal channel gain, and all the relay nodes apply equal normalized gain to their messages. That is, $|h_{R_n,D}|^2 = g_{R,D}$ $\forall n = 1, ..., N$

and $|A_n[k]|^2 = 1 \; \forall n = 1, ..., N$. Then, we have the following simplified expression for SNR:

$$\gamma_{D,R} = \frac{g_{R,D} N^2}{N_0} \quad (16)$$

Assuming that the distance between relays to destination is approximately the same as the distance between source and destination, we have $\gamma_{D,S} \approx g_{R,D}/N_0$. Then,

$$\gamma_{D,R} \approx N^2 \times \gamma_{D,S} \quad (17)$$

Therefore, the SNR at destination due to distributed relay beamforming with decode-and-forward relays is N^2 times the SNR at destination due to source node alone.

APPENDIX B
DERIVATION OF RULE OF THUMB IN (12)

Let us assume that all relay nodes achieve phase coherence at the destination node at time t_1, i.e., $\phi_n(t_1) = 0$ for all n, where $\phi_n(t_1)$ is the phase offset/error between relay R_n and destination at time t_1. Then, at a later time t_2, due to oscillator drift, the phases of all the relays are no longer aligned at the destination. Specifically, at time t_2, the beamforming power gain is:

$$G(t_2) = \left| \sum_{n=1}^{N} e^{j\phi_n(t_2)} \right|^2 \quad (18)$$

In clock literature, $\phi_n(t_2)$ are commonly modeled as $i.i.d$ Gaussian, i.e., $\phi_n(t_2) \sim N(0, \sigma_\phi^2)$ where σ_ϕ^2 is the phase error variance given as:

$$\sigma_\phi^2 = \sigma_{\phi,p}^2 + \sigma_{\phi,m}^2 \quad (19)$$

where $\sigma_{\phi,p}^2$ is the phase error variance due to process noise due to random walk frequency drift [4] and $\sigma_{\phi,m}^2$ is the phase error variance due to frequency offset measurement noise. Let $f_{SR} = f_c$, then $\beta = \frac{f_c}{f_{RD}}$. Then:

$$\sigma_{\phi,p}^2 = \frac{(2\pi f_c)^2 q_2^2 T_{delay}^3}{3\beta^2}, \sigma_{\phi,m}^2 = \frac{(2\pi)^2 \sigma_{f,m}^2 T_{delay}^2}{\beta^2} \quad (20)$$

where $T_{delay} = t_2 - t_1$ and $\sigma_{f,m}^2$ is the frequency error variance due to measurement noise. Assuming that the two-shot frequency estimator employed in Equation (6) in section IV-B1 meets CRLB, we have [18]:

$$\sigma_{f,m}^2 = \frac{1}{\pi^2 \gamma_1 T_{slot}^2} = \frac{1}{\pi^2 \gamma_1 M^2 T_{delay}^2}, \implies \sigma_{\phi,m}^2 = \frac{4}{\beta^2 M^2 \gamma_1}$$

where we have made use of the design principle, i.e., $T_{slot} = M \times T_{delay}$ from section III. Then, for aforementioned $i.i.d$ Gaussian assumption on phase errors and sufficiently large N, [20] provides us the following expression for mean beamforming gain:

$$E[G] = e^{-\sigma_\phi^2} N^2 + (1 - e^{-\sigma_\phi^2}) N \quad (21)$$

Then, to reap-off at least αN^2 power gain out of theoretical maximum gain N^2, we proceed as follows:

$$E[G] \geq e^{-\sigma_\phi^2} N^2 \geq \alpha N^2 \quad (22)$$

Putting the values of $\sigma_{\phi,p}^2$ and $\sigma_{\phi,m}^2$ in (22), and solving for T_{delay} we obtain the rule of thumb in (12).

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