## Joint Device Identification, Channel Estimation, and Signal Detection for LEO Satellite-Enabled Random Access

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Abstract - This spape peinvestigatest join to device identification, channel estimation, and signal detection for IdeO satellité enabled granti-freen abindom: aaccusse wheren aacmusti plehinput multipleoutput n(MIMO) system Willi Oorthogonal with neefrequency space modulations (OFES) distatible (OfFCs) mbattifice dynamics but the ternestrial-satelliteclinkt(TSIs) tWet divide (fb8 lrecewerl structure into i threet modules: i fürstt la dinear dnodul & for; identifying nactive devices ptwhich deverages when generalized approximate mediage passing (GAMP) algorithm togelitii/hatP inter-user interference to the delay. Doppler domain; second, a Don-linear module adopting then the sagen passing dalgorithm tonjointly estimate adjunitelment detect/transmit/signals; the third oided by Markovalandom field (MRF) valuar to explore the ethrer [Rin] ensioned block sparsity of channel cina the lodel asy-Doppter-language adomain the less of the Doppter-language and the less of the lose of the lose of the less of t tiogleis dexchanged diteratively obetween it hese lathree driodules obv beteful scheduling: Furthermorey the expectation in a ximization algorithm is rembedded tox learn the hyperparameters indeprior distributions; Simulation results pdemonstrate uthat sth Siproposed scheite doutperforms that ton ventionall solthods significantly lin termsnofo activity theorem significational nestimation activity, cand symboherror ratemation accuracy, and symbol error rate.

Index Terms—Random access, OTFS, satellite communications, message passing Dopplershiftt

## I.I.Introduction

Internet-of-Things: (Ioff) Tis proper the thatical segnation in next-generation-communications. Bresently, There are numere ans applications and teatlots devices to Ild be idistributed in rumoto regions, such as despris, ocuans, and derests behabut they are not supported by existing callular communication networks\_Fortunately,;low\_rearth\_orbit\_FLEQ)\_satellites\_possess lowitpropagationt delays lowspath dossirand elexible televation anglestomaking them stehighly promising solution to provide highay goverage, Inscholases, the inultiple access protocol plays cakey, tile in supporting efficient connectivity, key role in Grant free grantlem (accesse (GFRA) is considered to be suitabletforemachinortype communications, aspitiateduces osige nating loverhead and power consumption tands enhances access capability. Over the past few years many methods have been proposed for joint channel estimation and device identification inche terrestrial GERA systems li Eonex ample atherapproximate message apassing (AMP), was adopted Airs (Alesos address this problem a In 13 h pathogonal frequency division multiplexing (OFDM) was integrated into GFRA systems, and the gen-

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Symmetri Charinotastaand ilijöhjö Ottopitenstrenwith thit linterdisciplinkisy Geriterafyr (Secteritfor Reliability, Redliability (SnR), Thin te (StyT) of University of BSS darkembourg (SityLlarenthourg (Sityalka (Synteon Charinotas, bjymettersfeh) @imita), bjorn.ottersten (@imita). eral?zed multiple theasurement. Vec(8r, AMPowasaproposed to dxplorentherchaphed sparsity Dr. They as gulary dotted in 11 To Citriker improve, system performanced [2] httidl(2) adopted spreadings Based transmissioned themesland the signed one passing e type://algorithmino/Tointlythdentifyrdevices/testimateochannel, åfida addtect asigmate dTshoreabbivg-brenationech swoisks ob aveb ees designed of fordblocks fading a shapely evaluation is then assumed to rdmaiifycdustants during one eltransmission. (Howevergathe High ahobilitymefitldE@d satellite inevitablyerleads ignerapfdr changle 6fdtergestrialisatellitchlink (TSL)sandethet/langer/Dopplensthift, and the motion refudevises may incurrent negligible a Doppler spread: (?) shothlife which tanky classes outdated; (CSI and severe interscariales antel ferdice, (affil then debrades; the performance of dufrentialgorithmse/Thesereffects and the erbigablition delay should be takenhimo addiountmes garesultaddated terrestrial GFRA schemes raise not ediffectly capplicable to deligo detellite confirmations. Confacilitate transmissions eproconspension techniqueidil delaylelayoulid hooppken shifto may obertadopted befole, GERAnt but riesintisold@ERextsaheonsplexityn whithrentaly depress had battery sife of tremoter to Tirdevines, and fatelitast of a penvientional prehemose caunt our handlen the eDoppler spread effectivelypler shift may be adopted before GFRA, but it Orthogonals terror-drequencyxispacerl(tOTFS)), moleulation [A]; which operate of irectly in the Relay-Dopplem domain, has been proposedoasalasphomisingasolutidnatellallehiat@dholaforementionetivislanes. The location of nonzero element of effective chantelogorresponds-freethendelaypand DoppHer) shiftdofaéach physidalchath exhers the etwly contlitions are Dapplied dhat athe delayboand Dopplerl shift ano withing onbusymbol advertion and súbcamiertispaciniss respéctivelycaThereforeo itz és coeksiblet fof safellite to hastimate othes perfective of handelland at the Dodgt bet signalofwithout phrecionippasation an theeterrestrial dicities are {3}:afidd?};htwto GERAese;hemesl wlithpMIMOdOffFS:htave/bben proposed for d.E.Otsate littel: orbinaritations; iwhere the charmel distinution, and is ignals idetection sate liconsidered isoparately. Effectiver, thefacilitated brithmedesignistic, still beguine the terrostrialtileviaestlee precontpensalevfoesdelay[and/or Doppler ChifRictorbeGifRAvith MIMO-OTFS have been proposed forInLifi® papellitweconvestigatetijoiist device identificationl ebannali catimalisignand esignal ndetections ider let Geparataliste: Enabled GFRA a withere MIMO OFFS design opted to still dress the doubly: dispensive-effect and improve performance. Different from the strettions diteratified Awe assume that the IoT devices lacki global navigationi sutellige tsystemt (GNSS) i dapability i and do:noteleest to:precompedsatgrfor detaytand DoppHO shift! The satellitel Will Brandlehthern fill the Opling transmissibn antilltrus the complexity is and renergy fleon sumption pafoter restrial devices

ariffeeduced:oIn this scenarios thicepropagation delaynwillhib thereIdfländerecsymbol duration rand/eatther Dopplet shifts will be Nisse than louist subcarrier spacing, which brings that extra dhase antationrinler theifeffdctivesathalinel.wAs haardsult.hthe effectivered haknelaats reachioantenna (hurespresented) lexity three dimensionals (2dD) titens of, tandestinal taneously aris reclinded, the glether with the device activities and transmit high also forming a complicated non-linear signal/modele Forthermore, the chaintel tensor texhibitse 340 bilookespansitynin theide layi Doppler-angle (IDDA) domaionByrintroducisf@approprlatenaekiliAsy variables, the diffide whole detection as theme, into expression of the to talddress ithis piroblem 3 Delayerwise, device inculvity edetection (DDAd), teographic dwithanticle detrimention tiendesignal detection In the eDDAL, we handle eltereceived isignal Dalong the adelay dirtlensilela sulch phatr-theg 3D (Dhah)el otensor Banishe ospliting apperies roftmatrices, rands then the veen exalt zeth AMP (GAMP) algorithm is ead opted to edecouple the drank lnissions is frifferent deviges/inedifferent deltiy-Dopplete-dimensions AOtherwisbirthe sewere einter-tisert and inter-signier interfetience (WCF-Mile)riorate 810 spansitive impliquatity TESECESSIDefined like, iteals evol. Ale nonlinearlecoupling-covethesiggtis/litylostgtet, hehdeney cliefficient, and transmitt sightls obfaceh device, wherea spitsage passing afgorithmeis derivedtinga symbol-hyrsymbol Agsfifon (for yagh delayidimensiond Thee TSE omodule allopts the Markov random flieffer(MRH)e ticea piurel iffer 8 Dt blocky sparsityle of dhe edisionel OthorwByc, date fullyemicstageusehoduling tetheathries intodulies exchangle differsoft tenflormation with reachlighterheterates D until dendergened Furthermole, the expediation maximization (EM), algorithm isoeffibedded to detraitheil yperpalantelers in driving, where a message passing algorithm is derived in a symbol-by-symbol fashion for each delay dimension. The TSE module adopts the Markow Quetom field (MRF) to capture of land Dated specific confitted derive sterior with MINTOLOTES: The solutely importes throughout different devices that soft to fermations and without peter satemative which til equipped with a wriferm of an aban avere PA i of NaxinNzatiNo africhnalgemithen regenerativel paytoad temperteeromentosard propessing of baseband signals. In each time interval, each device shares the same time-frequency resources to transmit signal to the satellite with probability  $p_{\lambda}$ . In addition, we consider the scenario that the ground devices lack GNSS capabilityoFollowingDECresommendations of the RGPR-{21ein this section to resellite will firstly prepompensate a common delayeto tall t deviceso and other i handle, the differential delay and Doppler shift seewith the uplitak transmission. In the pext subsections/we first introduce the input-output relationship of the systems and then somulate the considered problems. In each time interval, each device shares the same timefrequency resources to transmit signal to the satellite with production the prapid validations of eTS las we consider the identity dispersivenchanneles Alacin Chis Swork all then. Red cadopt the spreading+baseibrschemene ?3GPP for giant-freestransmissibn anti-thic-OFDM-based-OFES: modulation: tonoombat they doubly dispersive reffect to hand IE She Specifically dislathened to ODEFS shaifteseg n=in0,t.he ,uQ linkl,tthensorth sidewich i is las signed switte ca tinique spréadingnéodd (C@ [kh/l], i/kput[-ou/h]/2t, relati@i/2tip-bf the-system, Mnd-thenwheren Mateanile Norare letted mumber nof

subtamiets Oathu OFDM tisymbols within one OTFS frame, respectively. Then, the information symbol  $\mathbf{t}_u[l]$  is spread into O frames, i.e., the transmitted signal in the delay Doppler domain is called the predefined alphabet  $A = \{a_1, \dots, a_l\}$  with cardinality  $A = \{a_1, \dots, a_l\}$  with the inner size  $A = \{a_1, \dots, a_l\}$  with the inner size  $A = \{a_1, \dots, a_l\}$  with the inner size  $A = \{a_1, \dots, a_l\}$  with  $A = \{a_1, \dots, a_l\}$  with  $A = \{a_1, \dots, a_l\}$  with a size  $A = \{a_1, \dots, a_l\}$  with a

$$\times \mathbf{P} \underbrace{\mathbb{D} \mathbb{B} \mathbb{A}^{\eta_{u}}}_{u,a_{v},a_{z}} \underbrace{\stackrel{V_{u}}{k} j_{1} \Pi_{N}}_{k} \underbrace{\stackrel{M-1}{\sum} - N \underbrace{\mathbb{Sym} \nu_{u}}_{y,u} \mathbf{D} \mathbf{\Phi} (\mathbb{B} T_{s} [k(\eta_{u}, \eta_{T})] \Gamma)}_{u,a_{v},a_{z}} \times \Pi_{N_{y}} (a_{y} - N_{y} \vartheta_{y_{u}} + \beta_{2}) \underline{\Pi}_{N_{z}} (a_{2} - N_{z} \vartheta_{z_{u},i}/2), \tag{2}$$

where  $h_{u,i}, \tau_u^* t_\mu$  and  $J_u'$  and  $J_u'$  and  $J_u'$  and  $J_u'$  the complex  $J_u'$  this ferential delay, and Doppler shift, respectively;  $\vartheta_{u_{\infty}}$  and  $\vartheta_{\text{effe}}$  i are the directional gosines along the acands raxis of UPA respects tively;  $M_{\odot}$  is the length of GPA T is one symbol duration. The symbol of t literature of the Neglective Hannel has Natleextra dimension related to the delay dimension to of the received signal, which results in the DD channel tensor at each antenna, since in the LEO satellite communications, the large differential delay and Depote the directional cosmes along the  $\eta^*$  and z axis of Depote shift usually cannot meet the conditions  $p_u, q' \in I$  and v are the estimator v and v and v and v and v and v are the estimator v and v and v and v are the estimator v and v and v are the estimator v and v are the estimator v and v and v are the estimator v and v and v and v are the estimator v and v are the estimator v and v and v are the estimator v and v and v are the estimator v and k' The q-th traine received from all devices can be represented and  $a_z \approx N_z \vartheta_{z_{u,i}}/2$ . Therefore, the channel in the delay-Doppler-angle domain shows the 3D-structured sparsity [?] Japaddition, unlike that in previous literature [?], the effective channel has an extra dimension related to the delay dimension l = 0 the received signal, which results in where  $D_{chain}$  the tectivity findication to father sintle devide. Lylich sateHileifoactinenand.tagns= Onetherwisdiffand:Zfat delsk, durd DAy(foler 2sh is: the aloyse aim then delay Hoppiditangle adomaiif. Note that the∆effective lchannel lof [eacHdevice tine (efficient 3D teitson as each auteura. To facilitate! the algorithm design,

We Becouple Fontoulaseout matrices by rewriting (??) as the

matrix form along the received delay dimension l, i.e.,

The q-th frame received from all devices can be represented as  $\mathbf{Y}_{q}^{l} = \mathbf{C}_{q}^{l}(\mathbf{T}^{l} \otimes \mathbf{I}_{N})(\Lambda \otimes \mathbf{I}_{MN})\tilde{\mathbf{H}}^{l} + \mathbf{Z}_{q}^{l}$ ,

block cifculative matrix due to the will be cifcular convolution  $G_{\rm p}/(2)$   $\sigma^2$  and the subjectivity solution  $G_{\rm p}/(2)$ Note that (the effective channel of each clevice (in (??)), is ar 3D denson lat each antenmer of facility tenths algorithm thatisk with the relation of vector of the thice man relations f?? \_astthermatrix formalong the received drawdine the identity matrix;  $\Lambda = \operatorname{diag}(\lambda)$ , where  $\lambda = [\lambda_0, \dots, \lambda_{U-1}]$ ;  $\begin{bmatrix} \mathbf{v}_{q} \mathbf{c}^{\mathsf{T}} \left( \mathbf{H}_{q}^{\mathsf{DDA}} \mathbf{c}^{\mathsf{T}} \mathbf{c}^{\mathsf{T}} \mathbf{c}^{\mathsf{T}} \mathbf{d}^{\mathsf{T}} \right) \mathbf{d}_{q} \\ \mathbf{v}_{1}^{\mathsf{T}} \mathbf{c}^{\mathsf{T}} \mathbf{$ GWMN, where vec(·) denotes the vectorization not having trix; the elements of Zivare independent Gaussian noises. We then collect all the received frames into a single matrix astrix due to the 2D circular tome in () in () in and its sub-matrix is the circulant matrix, formed by  $[\mathbf{C}_u^q[0,(l-l')_M],\mathbf{C}_u^q[1,(l-l')_M],\dots,\mathbf{C}_u^q[1,(l-l')_M]]$   $\mathbf{T}^l = \mathrm{diag}([\mathbf{t}_0^l,\dots,\mathbf{t}_{U-1}^l])$ where diag(x) returns  $(Y_0^l)$  diagonal matrix with the elements of vector  $\mathbf{x}_l$   $(Y_0^l)$  the main-diagonal  $\mathbf{t}_l^l$  =  $[\mathbf{t}_u^l(l)_M]$ ;  $(\mathbf{t}_l^l)_{l=1}^T [M + \mathbf{Y}_l)_M]$ , and  $(\mathbf{t}_l^l)_{l=1}^T [M + \mathbf{Y}_l^l]$  is and Henti ( $\Lambda$  matrix)  $\mathbf{H}^{l} = \operatorname{diag}(\lambda)$ , where  $\lambda = [\lambda_0, \dots, \lambda_{U-1}]$ ; th Next-to-clearly) alaborates the formulated problem and the proposed algorithm, we introduce some notations. Firstly,  $\mathbf{H}^l$  is partitioned as submatrices  $\mathbf{H}^{l,u} = \mathbf{H}^l[uMN^l]$   $(u \in \mathcal{H}^l)$ CMN, where celantemetric continues is the continues of th the themeth sole  $i\mathbf{Z}_q^t$  aton in the endeaved stetain at inversion  $W_t$ Those collomatic share or interpressing a single printitivas (l'+1)N-1,:  $\mathbf{Q} \in \mathbf{C}^{N \wr Na}(\mathbf{T}^{l}, \mathbf{Q}^{l}, \mathbf{T}^{l}) = 0$ .  $+\mathbf{Z}M-1$ , which is the channel of the l'-th grid in the delay dimension of the uth device.  $\mathbf{W}^{l}$  is partitioned simplarly, and then we get  $\mathbf{W}^{(0)}$ and  $\mathbf{W}^{l,u,l'}$  Finally, we collect all the transmitted information symbols as the vector  $\mathbf{t}_1 = (\mathbf{t}_0, \dots, \mathbf{t}_{U-Q})$  and collect all the charmers as  $\mathbf{HC}_Q^l[\mathbf{H}^{l'}]$ ... $\mathbf{HV}^{l-1}] = (\mathbf{T}^l \otimes \mathbf{I}_N)\mathbf{H}^l$ , and H'Te perform joint device identification, channel estimation and/signaltdetectionlywelresorate the Bayesian lapproach which acclist lprior distribution of the estimated dvariables reFiretty. two nadoptr shly, conditional rBeimoudli a Gaussian-triixtur H (GM) Histribution (\alpha \text{ehardeterize} the \text{ehardeter} \text{!.e., corresponding to} the channel matrix of the u-th device along the received l' = 0, ..., M - 1, which is the channel of the l'-th grid in the delay dimension of the u-th levice. W' is partitioned similarly, and then we get  $\mathbf{W}^{l,u}$  and  $\mathbf{W}^{l,u,l'}$ . Finally, we where K and  $(\omega_{L}^{l}, \mu_{L}, \phi_{u}^{l})$  are the number of components and collect all the transmitted information symbols as the parameters of GM, respectively  $h_{CU-1}$ , and collect all the l-th element vector  $\mathbf{t} = (l_{0}, \ldots, l_{U-1})$ , and collect all the l-th element l-th of  $\mathbf{H}^{l}(\mathbf{H}^{l})$ ,  $s_{i-1}^{l}(\mathbf{H}^{l}) \neq 1, -1$  is the corresponding support, and  $\delta$  (Tris the formac joint a function dTheir inverse dopth then Markov random field (MRE) priorations cribe the AD thlock sparsits of the charlest leason and their the support can be characterized variables. Firstly, we adopt the conditional Bernoulli

Batheidassicdsing (600cl alsstribution to characterize the channel, i.e.,

$$p\left( \mathbf{S}_{l,u,l}^{u,l'} \right) \underset{s_{i,j}}{\sim} \exp \left( \mathbf{S}_{i,j}^{u,l'} \right) \left( \sum_{i=0}^{N-1} s_{i,j}^{N_u-1} - \left( 1 \sum_{k=1}^{N-1} \sum_{j' \in \mathcal{D}_{i,j}^{u,l'}} \left( \sum_{k' \in \mathcal{U}_{i,j}^{u,l'}} \left( \sum_$$

and parameters of GM, respectively,  $h_{i,j}^{1,u,l^{i,j}}$  is the (i,j)-th where  $\text{nt}\psi(\beta H^i, s_{i',j'}^{u,l'})_{i,j}^{u,l'} \in \{\exp(\beta F_{j,i}^{u,l'} s_{i',j'}^{u,l'}) \cdot \text{comes positions}$ expoorts this is absurbortematic with (ion)-thetement adopt the Markov random field (MRF) prior to describe the 3D block sparsity of the channel tensor, and then the the neighbors infraction and syands class the parameter of MRF prior; a larger  $\beta$  implies a larger size of each block of

nonzeros, and a larger- $\alpha$  rencourages a sparser  $\mathbf{H}^{l,u,l'}$ . Based  $p\left(\mathbf{S}^{\mu,l'}\right) \propto \exp^{-it}$  $\exp(\beta s_{i,j}^{u,l}|s_{i',j'}^{u,l'}|_{L^1}\gamma(s_{i,j}^{u,l'})$ where support matrix with (i, j)-th

 $\exp($ set containing the neighbors of  $x_i^{u,t}$  and  $\alpha$  and  $\beta$  are the parameters of MRF prior: all  $\alpha$ size of each block of nouzeros, and a larger open courages a sparser  $\mathbf{H}^{l_{u,l'}}$ Based on (??)-(??), the maximum a

Pestimate for on (??)-(??), (W, H, t, S)(9)w.ek  $[\mathbf{W}^{0},...,\mathbf{W}^{M-1}], \mathbf{S}$  is r distribution is represented compo  $p(\mathbf{W}, \mathbf{H}, \mathbf{t})$ 

where  $p(\mathbf{W}^{l^{(1SE)}}\mathbf{H}^{l},\mathbf{t})$  corresponds to the constraints in (??), Fig. 1: Factor graph representation. given as

posteriori $_{\mathcal{D}}(\mathbf{MAP})_{\mathbf{H}}$ stėmat $_{\mathcal{C}}(\mathbf{W}^{l}(\mathbf{W}_{\mathbf{T}}\mathbf{H}_{\mathcal{S}}^{l})_{\mathbf{H}})$ given b $_{\mathbf{H}1}$ )

Then, the Weive devaces can be detected by the Snergy, detector) given by

where  $\mathbf{Y} = [\mathbf{Y}^0, \dots, \mathbf{X}_{d-1}^{M-1}], \mathbf{W} = [\mathbf{W}^0, \dots, \mathbf{W}^{M-1}], \mathbf{S}$  is composed  $\hat{\mathbf{g}}_u^t \mathbf{S}^u \mathbf{I}^t$  and  $\mathbf{W}^t \mathbf{e}^u \mathbf{p}$  esterior distribution 128 represented as

where  $\mathbb{I}_{\{H\}}$  is the Yndicator function and  $\xi_{th}$  is the predefined

threshold. Note that problem (??) is generally non-convex and difficult to solve. Since the variables to be estimated in (??) are all coupled together, an accurate message passing algorithm design pistchallenging of the process develop constonic complexity iteratives algorithm that could achieve near-optimal performance by utilizing a carefully designed receiver structure and sophisticated message updates. Additionally, the phase ambiguity problem [3] cinevitably attraction (??) this content dearned and information symbols are unknown in the receiver. Common methods for complating this problem include differential coding or asymmetric constellation [?] In this work (12) adopt the latter approach.

where III. JOHN the Dentice of Interest and the Eight Andron than problem. Detection and signal detection, are interested to get a graph of the problem of the eight detection, are interested to get a graph of the problem of the eight detection. The signal detection, are interested to get the eight of th

III. Variable nodes (With tis), depicted as white circles in Fig. ??, correspond to the variables with the same names in (??)-(??).

In Cheek needes (f'ye (grosset), then postnessed as there for joint adevise riger in cation pother with estimation fund signal of trees, constitut the sactor committees introduced for describing the probability if transfulle ware boilt of 3: Then espectively. The edge message passes between a variable type note and a scheen and when the variable the involved on distribution of constraint, and the EM algorithm is embedded to learn the unknown hyperparameters in the prior in addition, as shown in Fig. ??, we divide the whole receiver distribution structure into three modules: DDAI module for the linear  $\operatorname{signpl}_{\operatorname{a}}$  cmodel  $\operatorname{rip}_{\operatorname{I}}(R)$  parallel along the received delay dimension *l*, which is adopted to identify active devices. Simultaneously, if decouples the transmissions 77, which consists of two types of nodes: different devices. CCES printed who desired so that is not the particular with the circles which takes the comparent the stages of DDAI though and refined messing 63 of (TSE module as input, and then jointly performs charmel estimation and signal detection of SE mount for the MRK prior nebrisiders Fibe messages menerated the CCESTS thougher and texplores the 3D stock tsparsity of the Then, one it in near the shall be density of the certain and the certain the shall be a shall moduled The massages pare passed between the three thoughts iterativeryami passes between a variable node and a check node when the variable is involved in the check

## B. PestasieniDistribution Estimation

In In difficiosubsection, wwith the known why perparameters; hove describe how thermessages iterate obstween the Athree modules the getriber fisighest imode in, and The layperparameters a will We ppdated latengentine following delatent invention of Athres the

and spaged from inductive to artive step with a DSA introduction of the control o

B. Posterior Abistribution Estimation  $h_{i,j}^{l,u,l'} = \sum_{j=1}^{N} \frac{1}{j} \frac{1}{j}$ 

With the inputs  $\Delta_{i,j}^{g_i,u,t'}(s_{i,j}^{g_i,j})$ , we are now ready to describe the tree stages involved in the MRF. To creatly characterize the runave posterior, the left Grant Propanith bottom religious constitution of the remarks of the respective the respective to the respective to the respective to the respective to the respective respective to the respective respective to the respective respect

input message of  $s_{i,j}^{u,l'}$  can be represented as  $\Omega_{i,j}^{L^{u,l'}} \propto \int_{\Delta_{i,j',j'}^{u,j'}} \prod_{t=0}^{M-\lfloor A \rfloor} \sum_{j=1,...,l}^{d-\lfloor A \rfloor} \prod_{j=1,...,l}^{d-\lfloor A \rfloor} \prod_{j=1$ 

 $\int_{\sim s_{i,j}^{u,l'}} \prod_{l=0}^{M-1} \Delta \frac{e_{i,j}^{l,u,l'}}{s_{\overline{i}\overline{j}}^{u,l'}} \sum_{\substack{p \in \{u,l'\}\\ \overline{p} \ m,i,j}} \Omega_{i,jL}^{p^{u,l'}} \gamma(s_{i,jL}^{u,l'}) \psi(s_{i,j}^{u,l'},s_{i,jL}^{u,l'}) \\ \text{where } \sim s_{i,j}^{u,l'} \text{ represent the variables except } s_{i,j}^{u,l'}. \text{ The }$ 

Given the inputs messages for the right + top, the obttour essage of it is given by  $\Omega_{i,j}^{L^{u,l'}}$ . Then, the output message of

$$S_{i,j}^{u,l'} \overset{\text{is given by}}{\Delta} \overset{\text{is given by}}{\underset{j,u,l'}{\delta}} = \sum_{\substack{|\mathcal{A}|\\ p}} \overset{|\mathcal{A}|}{\underset{m,j,j}{\delta}} \overset{\text{is given by}}{\delta} (t_{(l-l')_M + uM} - a_m), \quad (19)$$

$$\Delta \overset{l,u,l'}{\underset{j,u,l'}{\delta}} \propto \gamma (s_{i,j}^{u,m}) \prod_{j=1}^{m} \Delta \overset{e_{i,j}}{\underset{s_{u,l'}}{\delta}} \prod_{j=1}^{m} \Omega^{p^{u,l'}}_{i,j}. \quad (16)$$
where  $\overset{\text{is given by}}{p}_{m,i,j}$  is updated by the product of all the probability

The refined inessages of H after exploring the 3D block sparsity will be fed back to the CCESD module given by and  $\Delta_{g_{i,j}, h_i^{-l', M+uM}}^{l_{(l-l')}, M+uM}$ , the message of feedback from CCESD module to DDAf is the Bernoulli  $p_{i,j}^{-l', M+uM}$  given by

$$\begin{aligned} & \text{Widn}_{w_{i,j}^{l,u,l'}}^{g_{i,j}^{l,u,l'}} \int_{\mathbf{x},u'} \sum_{d',j} \sum_$$

$$\Delta \sum_{m=1}^{|\mathcal{A}|} p^{l, \mathbf{y}} p^{l, \mathbf{y}, \mathbf{p}} (t_{i, j}^{l, \mathbf{y}, \mathbf{p}'}, t_{i, j}^{l, \mathbf{y}, \mathbf{p$$

Similarly, the posterior distribution of  $h^{l,u,l'}_{j,j+u,M}$ , also approximated as a Bernoullie  $GM_V$  distribution given by

$$\Delta_{g_{i,j}^{l,u,l'}}^{t_{(l-l')_M+uM}} \stackrel{\Delta}{=} \sum_{j}^{|\mathcal{A}|} \stackrel{\mathcal{A}}{p} \stackrel{\mathcal{A}}{m}_{m,i,j}^{i,j} \stackrel{\mathcal{A}}{\otimes} t_{l,u,l'}^{l,u,l'} \stackrel{\mathcal{A}}{\sim} t_{i,j}^{l,u,l'}. \tag{22}$$

We can also get the approximated posterior distribution of information symbola ased by the product of all the probabil-

ity related to  $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$  and  $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$  and  $\Delta_{t,u,l'}^{l,u,l'}$  and  $\Delta_{t,u,l'}^{l,u,l'}$  and  $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$  and  $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$   $\Delta_{t,u,l'}^{l,u,l'}$  $\sqrt[g]{dr} S p_{ij} h' d d a | \sqrt[g]{dr} p_{ij} h' | \sqrt[g]{dr} p_{ij} h' | \sqrt[g]{dr} h'$ with respect to the approximated posterior distribution will be inputted to the GAMP for next iteration. After the algorithm converges, the estimation of  $h_{i,j}^{l,u,l'}$  is given by its mean with respect to  $(??)_{i,i,e}$ ,  $\hat{h}_{i,j,u,l'}^{l,u,l'} = \mathrm{E}[h_{i,j}^{l,u,l'}|\mathbf{Y}]$ . Based on (??), we perform symbol-by-symbol MAP estimation for information symbols as Now, the posterior distribution of  $w_{i,j}^{l,u,l'}$  is approximated as a Bernoully  $G_{i,j}^{l,u,l'}$  distribution by  $C_{i,j}^{l,u,l'}$  by the increase  $C_{i,j}^{l,u,l'}$ messages of it given by  $a \in A$ 

C. Learning the Hyperparameters' with unit

We now adopt EM algorithm to learn the prior parameters  $\mathbf{q}\triangleq\{\sigma^2,[\omega_u]_{u=0}^{U-1},[\mu_u]_{u=0}^{U-1},[\phi_u]_{u=0}^{U-1}\}. \text{ The EM algorithm is an identity technique that increases is lower bound on the like$ nnocinatescus rerbuonould in Mudicasily thio hyperparameters

are updated in the *i*-th iteration as 
$$A_{i,j}^{l,w,l'} = A_{i,j}^{l,w,l'} \times A_{i,j}^{l$$

We can also get the approximated posterior distribution of information symbols as  $p(\mathbf{H}, \mathbf{S}, \mathbf{Y} | \mu_k) | \mathbf{Y}, \mathbf{q}$ , (26)

$$(\phi_k^u)^{i+1} = \arg \max_{\mathbf{x} \in \mathbb{E}} [\log p_i(\mathbf{H}, \mathbf{S}, \mathbf{Y} \mid \phi_k^u) \mid \mathbf{Y}, \mathbf{q}^i],$$
 (27)

$$\begin{array}{l} (\phi_k^u)^{i+1} = \arg\max_{\boldsymbol{\Phi}} \mathbb{E}[\log p\left(\mathbf{H},\mathbf{S},\mathbf{Y}\mid\phi_k^u\right)\mid\mathbf{Y},\mathbf{q}^i], & (27) \\ \frac{\Delta_t}{(l_i-l_i^t)_M} = \arg\max_{\boldsymbol{\Phi}} \mathbb{E}[\log p\left(\mathbf{H},\mathbf{S},\mathbf{Y}\mid\phi_k^u\right)\mid\mathbf{Y},\mathbf{q}^i], & (23) \\ (\omega_k^u)^{i+1} = \arg\max_{\boldsymbol{\Phi}} \mathbb{E}[\log p\left(\mathbf{H},\mathbf{S},\mathbf{Y}\mid\omega_k^u\right)\mid\mathbf{Y},\mathbf{q}^i], & (28) \end{array}$$

where R. TI, and S. are related as heidden variables the expece tation is with respect to the posterior distribution approximated hysthe aforementioned message passing type algorithm, and Werdennie ARter the algoriRhm converges the StWhatiBN exantining the first iderivative of the objective function with respect to the variables in (??)-(??), we can get the updates of the set hyperparameters. The detailed derivation is solithed bere you billined spacing atom for information symbols as

The MRF-GM-AMP algorithm can be summarized as (for lows: Firstly, the DDAI module adopts the GAMP algorithm to output the message of W in (??) given Y and C. Then, the CCESD module generates the initial message of S using (??) and (??) based on the output message by DDAI. Then, the TSE module updates the message of H using (??) and (??) donexploitoits BM block aparsity land, feeds back the refined message to the OCESD, module Arthe same tipe, the message of ties undated using the and the same tipe. posterior distribution for (Weath their computed using (22) (??) hand the estimated distribution of Whis used for the next iteration of the GAMP algorithm. Next, the hyperparameters are applated using 4937-P(19) The Publive steps are repeated (146) convergence. Finally, information symbols and the estimated channel are given by (??) and the expectation with respect to (??), respectively, and the active devices can be detected according to (??). The complexity of the algorithm is mainly from the  $+G\Delta MP_g$  algorithm and the mossage passing updates with a total complexity of  $O(QUMN^2N_a + |\mathcal{A}|KUMNN_a)$ , which in linear ain the number of users and thus suitable for random access in LEO satellite communications distribution approximated by the afforcementioned message passing-type algorithm, and we denote  $R = [R^0, ..., R^{M-1}]$  with R in this section, we demonstrate the performance of the proposed algorithms through computer simulations. We consider objective function with respect to the variables in (1) the scenarios of the non-terrestinal networks recommended by the scenarios of the inon-terrestinal networks recommended by the 3GPP; [7] where the satellite operates at S band with the detailed derivation is omitted here for limited spacing. 15 Tally where the satellite operates at S band with the detailed derivation is omitted here for limited spacing. The MRF-GM-AMI algorithm can be stimiliarized as power delay profile of channel complex gain follows the NTNs approximation of the same second complex gain follows the NTNs. power delay profile of channel complex gain follows the NTN TDL the differential delay (ms) is uniformly selected from a gorithm to output the message's uniformly selected from 10.4 44, and the Dopplers shift (kHz) is uniformly selected from 1-41, and the Dopplers shift (kHz) is uniformly selected from 1-41, we consider the sporadic transmissions that message by potential receives with \$21 no active upgates the message by 100A1. Then, the TSE income lightes the and the active decrees transmit consecutive OTFS trames with message of Musing the same transmit consecutive OTFS trames with the sparsity and feeds and the refined message to the monarcealist pulse amplitude modulation. They the message of is adopted for solving phase ambiguity and the elements of ispreading code using the sparse of the solving phase ambiguity and the elements of ispreading code using the sparsity and the solving phase ambiguity and the elements of ispreading code using the sparsity and the solving phase ambiguity and the solving phase ambiguity and the solving the sparsity and the solving the sparsity and the solving the sparsity and the spar obey fix 0 s complited using define the received signal to doitei battions of NRV =is10dogd for the tree wand the tiverage tlevice Addivity Igorithmate NexER the they average mormalized medatsquareit-griof? (NMSE)Tlandshhereaverage asymbotecorol rateil(SER)eageradopFed alsy metficsuforiodeviceulideatification; entimeteestimation, and signal brefection udes bectively charten with respect to (22), respectively and the active devices by AER active according to (22). The majorithms of and SERrithy is mainly front, the level assumed that and thactivesdegices transmit pleates for other natural heast Rexity of O FOX M2 NF1 No.27, Jack Fright No. Compare idevice lidentification; chanbel estimation and signal detection operformance between the Orsposeitealgorithm and benchmarks, respectively. Here,

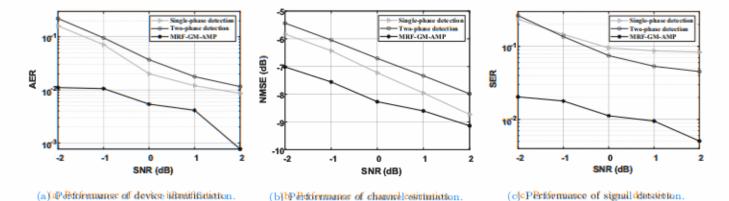


Fig. 2: Performance comparisons between the single-phase detection etwo-phase detection and tMRFaGM-MMP, under different SNR in a local stress of the solution of the solutio

the single-phase method adopts the Ramel transmission scheme as ours, and the ConvSBL-GAMP [?] is used to estimate W<sup>t</sup> firstly, third therican energy monestories altopication mener the than surrece infortisation by inforcing the two printers crience adopts the convision to amprovious of the consideration and works acovernes blacether Gan Railter boots, have the little of AND attectorus autibilă le decece un confine or svin sons du film afaltit tile personamer delike profilsed agbannal formales with the SNR, hand and a Day but performs fine two benefitmants, is meniformicated enterefrees vends 44 of and throposed activities fbHz)EO vatifimerbased-utstihkfreransmission in Viceseneider the range a differentiam itsiays and a bobbier strent 40 noncentral denventional separated detection scheme has a night error tion for SER; then sent can sary tupp of I f Small man bet of Gevices. On the biner hand, the proposed inter-company works were THIS IS VICE IN MEDICAL TO BE TO THE PROPERTY OF JOINT CONTROL THE PROPERTY OF THE PROPE solving on a sed ambiguitate and the iglement a commerce who is and Alekers around too). if it is all y?? whe brooked argorithm bas about 3 dBreein in terms of SNR and in FB ?? ather proposed algorithm always has 1 dB and A dB gain compared with the single-phase and two-phase detection, respectively. In Fig. 1331 when the SER is around 10.05 the proposed algorithm numericans of behavior benchmarks, by dropped that et idle; readdition, the SER of MRE-GMrAMP-is below 0.05 when the spectively given by AFR SNR is greater than -2 dB, which indicates that the proposed algorithm could work well in the low SNR regime, and thus is suitable for the satellite communications.
we assume that the inactive devices transmit zero for

Fig. ??, Fig. ??, and Fig. ?? compare device identification flishword develoption, joids developted a joids

for LEO satellite-based uplink transmission in presence of the large differential delay and Doppler shift. Notice that conventional separated detection scheme has a high error floor for SER; hence it can only support a small number of devices. On the other hand, the proposed MRF-GM-AMP works well. This is due to the benefit of joint device identification, channel estimation, and signal detection design. For example, when the AER is around 0.01 in Fig. ??, the proposed algorithm has about 3 dB gain in terms of SNR, and in Fig. ??, the proposed algorithm always has 1 dB and 2 dB gain compared with the single-phase and two-phase detection, respectively. In Fig. ??, when the SER is around 0.05, the proposed algorithm outperforms the two benchmarks by more than 4 dB. In addition, the SER of MRF-GM-AMP is below 0.05 when the SNR is greater than -2 dB, which indicates that the proposed algorithm could work well in the low SNR regime, and thus is suitable for the satellite communications.

## V. Conclusion

This work developed a joint device identification, channel estimation, and signal detection scheme for MIMO-OTFS-based GFRA in LEO satellite communications, where both the large differential delay and Doppler shift exist. To provide low-complexity yet near-optimal estimation and exploit the 3D-structured sparsity of the channel in the delay-Doppler-angle domain, we proposed a message passing-type approach with MRF prior and carefully designed receiver structure. Simulation results demonstrate that the proposed algorithm outperforms conventional algorithms significantly, with a linear complexity in the number of devices and the ability to operate in the low SNR regime, making it suitable for random access in LEO satellite communications.