



## Distances on a measure (affine ordered hovel)

Auguste Hébert

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# Distances on a measure

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## Abstract

A measure (also known as an affine ordered hovel)  $\mathcal{I}$  is a generalization of the Bruhat-Tits building that is associated to a split Kac-Moody group  $G$  over a nonarchimedean local field. This is a union of affine spaces called apartments. When  $G$  is a reductive group,  $\mathcal{I}$  is a building and there is a  $G$ -invariant distance inducing a norm on each apartment. In this paper, we study distances on  $\mathcal{I}$  inducing the affine topology on each apartment. We construct distances such that each element of  $G$  is a continuous automorphism of  $\mathcal{I}$  and we study their properties (completeness, local compactness, ...).

## Contents

|          |   |           |
|----------|---|-----------|
| <b>1</b> | <b>Introduction</b>   | <b>2</b>  |
| <b>2</b> | <b>Masures</b>  | <b>4</b>  |
| 2.1      | Root generating system . . . . .  | 4         |
| 2.2      | Vectorial faces and Tits preorder . . . . .                             | 5         |
| 2.3      | Metric properties of $W^v$ . . . . .                                    | 5         |
| 2.4      | Filters and enclosure . . . . .   | 5         |
| 2.5      | Face, sector-faces, chimneys and germs . . . . .                        | 6         |
| 2.6      | Measure . . . . .   | 7         |
| 2.7      | Retractions centered at sector-germs . . . . .                          | 8         |
| 2.8      | Parallelism in $\mathcal{I}$ . . . . .                                  | 8         |
| <b>3</b> | <b>Splitting of apartments</b>  | <b>9</b>  |
| 3.1      | Splitting of apartments in two half-apartments . . . . .                | 9         |
| 3.2      | Splitting of apartments . . . . .                                       | 12        |
| 3.3      | Restrictions on the distances . . . . .                                 | 13        |
| <b>4</b> | <b>Distances of positive type and of negative type</b>                  | <b>15</b> |
| 4.1      | Translation in a direction . . . . .                                    | 15        |
| 4.2      | Definition of distances of positive type and of negative type . . . . . | 16        |
| 4.3      | Study on the apartments containing $\mathfrak{s}$ . . . . .             | 16        |
| 4.4      | Geodesics in $\mathcal{I}$ . . . . .                                    | 18        |
| 4.5      | Equivalence of the distances of positive type . . . . .                 | 19        |
| 4.6      | Study of the action of $G$ . . . . .                                    | 21        |
| 4.7      | Case of a building . . . . .  | 22        |

|          |  |           |
|----------|--|-----------|
| <b>5</b> | <b>Mixed distances</b>   | <b>23</b> |
| 5.1      | Comparison of positive and negative topologies . . . . .                 | 23        |
| 5.2      | Mixed distances . . . . .  | 24        |
| 5.3      | Link with the initial topology with respect to the retractions . . . . . | 24        |
| 5.4      | A continuity property for the map $+_{+\infty}$ . . . . .                | 26        |
| <b>6</b> | <b>Contractibility of <math>\mathcal{I}</math></b>                       | <b>28</b> |

# 1 Introduction

If  $G$  is a split Kac-Moody group over a nonarchimedean local field, Stéphane Gaussent and Guy Rousseau introduced a space  $\mathcal{I}$  on which  $G$  acts and they called this set a “measure” (or an “affine ordered hovel”), see [GR08], [Rou17]. This construction generalizes the construction of the Bruhat-Tits building associated to a split reductive group over a field equipped with a nonarchimedean valuation made by François Bruhat and Jacques Tits, see [BT72] and [BT84]. A measure is an object similar to a building. It is a union of subsets called “apartments”, each one having a structure of a finite dimensional real-affine space and an additional structure defined by hyperplanes (called walls) of this affine space. The group  $G$  acts transitively on the set of apartments. It induces affine maps on each apartment, sending walls on walls. We can also define sectors and retractions from  $\mathcal{I}$  onto apartments with center a sector-germ, as in the case of Bruhat-Tits buildings. However there can be two points of  $\mathcal{I}$  which do not belong to a common apartment. Studying  $\mathcal{I}$  enables one to get information on  $G$  and this is one reason to study measures.

In this paper, we assume the valuation of the valued field to be discrete. Each Bruhat-Tits building  $BT$  associated to a split reductive group  $H$  over a field equipped with a discrete nonarchimedean valuation is equipped with a distance  $d$  such that  $H$  acts isometrically on  $BT$  and such that the restriction of  $d$  to each apartment is a euclidean distance. These distances are important tools in the study of buildings. We will show that we cannot equip measures which are not buildings with distances having these properties but it seems natural to ask whether we can define distances on a measure which:

- induce the topology of finite-dimensional real-affine space on each apartment,
- are compatible with the action of  $G$ ,
- are compatible with retractions centered at a sector-germ.

We show that under the assumption of continuity of retractions, the metric space we have is never complete nor locally compact (see Subsection 3.3). We show that there is no distance on  $\mathcal{I}$  such that the restriction to each apartment is a norm. However, for each sector-germ  $\mathfrak{s}$  of  $\mathcal{I}$ , we construct distances having the following properties (Corollary 4.17, Lemma 4.6, Corollary 4.18 and Theorem 4.22):

- the topology induced on each apartment is the affine topology,
- each retraction with the center  $\mathfrak{s}$  is 1-Lipschitz continuous,
- each retraction with center a sector-germ of the same sign as  $\mathfrak{s}$  is Lipschitz continuous,
- each  $g \in G$  is Lipschitz continuous when we regard it as an automorphism of  $\mathcal{I}$ .

We call them *distances of positive* or *of negative type*, depending on the sign of  $\mathfrak{s}$ . We prove that all distances of positive type on a measure (resp. of negative type) are equivalent, where two distances  $d_1$  and  $d_2$  are said to be equivalent if there exist  $k, \ell \in \mathbb{R}_{>0}$  such that  $kd_1 \leq d_2 \leq \ell d_1$  (this is Theorem 4.16). We thus get a *positive topology*  $\mathcal{T}_+$  and a *negative topology*  $\mathcal{T}_-$  defined by distances of  $\pm$  types. We prove (Corollary 5.4) that these topologies are different when  $\mathcal{I}$  is not a building. When  $\mathcal{I}$  is a building these topologies agree with the usual topology on a building (Proposition 4.23).

Let  $\mathcal{I}_0$  be the  $G$ -orbit in  $\mathcal{I}$  of some special vertex. If  $\mathcal{I}$  is not a building,  $\mathcal{I}_0$  is not discrete for both  $\mathcal{T}_-$  and  $\mathcal{T}_+$ . We also prove that if  $\rho$  is a retraction centered at a negative (resp. positive) sector-germ,  $\rho$  is not continuous for  $\mathcal{T}_+$  (resp.  $\mathcal{T}_-$ ), see Proposition 5.3. For these reasons we introduce *mixed distances*, which are sums of a distance of positive type with a distance of negative type. We then have the following (Theorem 5.6): all the mixed distances on  $\mathcal{I}$  are equivalent; moreover, if  $d$  is a mixed distance and  $\mathcal{I}$  is equipped with  $d$  then:

- each  $g : \mathcal{I} \rightarrow \mathcal{I} \in G$  is Lipschitz continuous,
- each retraction centered at a sector-germ is Lipschitz continuous,
- the topology induced on each apartment is the affine topology,
- the set  $\mathcal{I}_0$  is discrete.

The topology  $\mathcal{T}_m$  associated to mixed distances is the initial topology with respect to the retractions of  $\mathcal{I}$  (see Corollary 5.10).

We prove that  $\mathcal{I}$  is contractible for  $\mathcal{T}_+$ ,  $\mathcal{T}_-$  and  $\mathcal{T}_m$ .

Let us explain how to define distances of positive or negative type. Let  $\mathbb{A}$  be the standard apartment of  $\mathcal{I}$  and  $C_f^v$  be the fundamental chamber of  $\mathbb{A}$ . Let  $\mathfrak{s}$  be a sector-germ of  $\mathcal{I}$ . After applying some  $g \in G$  to  $A$ , we may assume  $A = \mathbb{A}$  and that  $\mathfrak{s}$  is the germ  $+\infty$  of  $C_f^v$  (or of  $-C_f^v$  but this case is similar). Fix a norm  $|\cdot|$  on  $\mathbb{A}$ . For every  $x \in \mathcal{I}$ , there exists an apartment  $A_x$  containing  $x$  and  $+\infty$  (which means that  $A_x$  contains a sub-sector of  $C_f^v$ ). For  $u \in \overline{C_f^v}$ , we define  $x + u$  as the translate of  $x$  by  $u$  in  $A_x$ . If  $u$  is chosen to be sufficiently dominant,  $x + u \in C_f^v$ . Therefore, for all  $x, x' \in \mathcal{I}$ , there exist  $u, u' \in C_f^v$  such that  $x + u = x' + u'$ . We then define  $d(x, x')$  to be the minimum of the  $|u| + |u'|$  for such couples  $u, u'$ .

We thus obtain a distance for each sector-germ and for each norm  $|\cdot|$  on  $\mathbb{A}$ .

This paper is organized as follows.

In Section 2, we review basic definitions and set up the notation.

In Section 3, we show that if  $\mathfrak{s}$  is a sector-germ of  $\mathcal{I}$ , we can write each apartment as a finite union of closed convex subsets each of which is contained in an apartment  $A$  containing  $\mathfrak{s}$ . The most important case for us is when  $A$  contains a sector-germ adjacent to  $\mathfrak{s}$ . We then can write  $A$  as the union of two half-apartments, each contained in an apartment containing  $\mathfrak{s}$ . We conclude Section 3 with a series of properties that distances on  $\mathcal{I}$  cannot satisfy.

In Section 4, we construct distances of positive and negative type on  $\mathcal{I}$ . We prove that all the distances of positive type (resp. negative type) are equivalent. We then study them.

In Section 5, we first show that when  $\mathcal{I}$  is not a building,  $\mathcal{T}_+$  and  $\mathcal{T}_-$  are different. Then we define mixed distances and study their properties.

In Section 6, we show that  $\mathcal{I}$  is contractible for the topologies  $\mathcal{T}_+$ ,  $\mathcal{T}_-$  and  $\mathcal{T}_m$ .

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## 2 Masures

In this section, we review the theory of masures. We restrict our study to semi-discrete masures which are thick of finite thickness and such that there exists a group acting strongly transitively on them (we define these notions at the end of the section). These properties are satisfied by masures associated to split Kac-Moody groups over nonarchimedean local fields (see [Rou16]). To avoid introducing too much notation, we do not treat the case of almost split Kac-Moody groups (see [Rou17]). By adapting Lemma 3.1, one can prove that our results remain valid in the almost split case.

We begin by defining the standard apartment. References for this section are [Kac94], Chapter 1 and 3, [GR08] Section 2 and [GR14] Section 1.

### 2.1 Root generating system

A Kac-Moody matrix (or generalized Cartan matrix) is a square matrix  $C = (c_{i,j})_{i,j \in I}$  with integer coefficients, indexed by a finite set  $I$  and satisfying:

1.  $\forall i \in I, c_{i,i} = 2$
2.  $\forall (i,j) \in I^2 | i \neq j, c_{i,j} \leq 0$
3.  $\forall (i,j) \in I^2, c_{i,j} = 0 \Leftrightarrow c_{j,i} = 0$ .

A root generating system is a 5-tuple  $\mathcal{S} = (C, X, Y, (\alpha_i)_{i \in I}, (\alpha_i^\vee)_{i \in I})$  made of a Kac-Moody matrix  $C$  indexed by  $I$ , of two dual free  $\mathbb{Z}$ -modules  $X$  (of characters) and  $Y$  (of co-characters) of finite rank  $\text{rk}(X)$ , a family  $(\alpha_i)_{i \in I}$  (of simple roots) in  $X$  and a family  $(\alpha_i^\vee)_{i \in I}$  (of simple coroots) in  $Y$ . They have to satisfy the following compatibility condition:  $c_{i,j} = \alpha_j(\alpha_i^\vee)$  for all  $i, j \in I$ . We also suppose that the family  $(\alpha_i)_{i \in I}$  (resp.  $(\alpha_i^\vee)_{i \in I}$ ) freely generates a  $\mathbb{Z}$ -submodule of  $X$  (resp. of  $Y$ ).

We now fix a Kac-Moody matrix  $C$  and a root generating system with the matrix  $C$ .

Let  $\mathbb{A} = Y \otimes \mathbb{R}$ . We equip  $\mathbb{A}$  with the topology defined by its structure of a finite-dimensional real-vector space. Every element of  $X$  induces a linear form on  $\mathbb{A}$ . We will regard  $X$  as a subset of the dual  $\mathbb{A}^*$  of  $\mathbb{A}$ : the  $\alpha_i, i \in I$  are viewed as linear forms on  $\mathbb{A}$ . For  $i \in I$ , we define an involution  $r_i$  of  $\mathbb{A}$  by  $r_i(v) = v - \alpha_i(v)\alpha_i^\vee$  for all  $v \in \mathbb{A}$ . Its fixed points set is  $\ker \alpha_i$ . The subgroup of  $\text{GL}(\mathbb{A})$  generated by the  $r_i, i \in I$  is denoted by  $W^v$  and is called the *Weyl group* of  $\mathcal{S}$ . The system  $(W^v, \{r_i | i \in I\})$  is a Coxeter system.

Let  $Q = \bigoplus_{i \in I} \mathbb{Z}\alpha_i$  and  $Q^\vee = \bigoplus_{i \in I} \mathbb{Z}\alpha_i^\vee$ . The groups  $Q$  and  $Q^\vee$  are called the *root lattice* and the *coroot-lattice*.

One defines an action of the group  $W^v$  on  $\mathbb{A}^*$  as follows: if  $x \in \mathbb{A}, w \in W^v$  and  $\alpha \in \mathbb{A}^*$  then  $(w.\alpha)(x) = \alpha(w^{-1}.x)$ . Let  $\Phi = \{w.\alpha_i | (w, i) \in W^v \times I\}$  be the set of *real roots*. Then  $\Phi \subset Q$ . Let  $Q^+ = \bigoplus_{i \in I} \mathbb{N}\alpha_i, Q^- = -Q^+, \Phi^+ = \Phi \cap Q^+$  and  $\Phi^- = \Phi \cap Q^-$ . Then  $\Phi = \Phi^+ \cup \Phi^-$ . The elements of  $\Phi^+$  (resp.  $\Phi^-$ ) are called the *real positive roots* (resp. *real negative roots*). Let  $W^a = Q^\vee \rtimes W^v \subset \text{GA}(\mathbb{A})$  be the *affine Weyl group* of  $\mathcal{S}$ , where  $\text{GA}(\mathbb{A})$  is the group of affine automorphisms of  $\mathbb{A}$ .

For  $\alpha$  and  $k \in \mathbb{R} \cup \{+\infty\}$ , one sets  $D(\alpha, k) = \{x \in \mathbb{A} | \alpha(x) + k = 0\}, D^\circ(\alpha, k) = \{x \in \mathbb{A} | \alpha(x) + k > 0\}$  and  $M(\alpha, k) = \{x \in \mathbb{A} | \alpha(x) + k = 0\}$ . A *wall* (resp. a *half-apartment*) of  $\mathbb{A}$  is a hyperplane (resp. a half-space) of the form  $M(\alpha, k)$  (resp.  $D(\alpha, k)$ ) for some  $\alpha \in \Phi$  and  $k \in \mathbb{R}$ . The wall (resp. half-apartment) is said to be a *true wall* (resp. a *true half-apartment*) if  $k \in \mathbb{Z}$  and a *ghost wall* if  $k \notin \mathbb{Z}$ . This choice of true walls means that the apartment (or the masure) is semi-discrete.

## 2.2 Vectorial faces and Tits preorder

### Vectorial faces

Define  $C_f^v = \{v \in \mathbb{A} \mid \alpha_i(v) > 0, \forall i \in I\}$ . We call it the *fundamental chamber*. For  $J \subset I$ , one sets  $F^v(J) = \{v \in \mathbb{A} \mid \alpha_i(v) = 0 \forall i \in J, \alpha_i(v) > 0 \forall i \in I \setminus J\}$ . Then the closure  $\overline{C_f^v}$  of  $C_f^v$  is the union of the subsets  $F^v(J)$  for  $J \subset I$ . The *positive* (resp. *negative*) *vectorial faces* are the sets  $w.F^v(J)$  (resp.  $-w.F^v(J)$ ) for  $w \in W^v$  and  $J \subset I$ . A *vectorial face* is either a positive vectorial face or a negative vectorial face. We call a *positive chamber* (resp. *negative*) every cone of the form  $w.C_f^v$  for some  $w \in W^v$  (resp.  $-w.C_f^v$ ). By Section 1.3 of [Rou11], the action of  $W^v$  on the set of positive chambers is simply transitive. The *Tits cone*  $\mathcal{T}$  is defined as the convex cone  $\mathcal{T} = \bigcup_{w \in W^v} w.\overline{C_f^v}$ . We also consider the negative cone  $-\mathcal{T}$ .

### Tits preorder on $\mathbb{A}$

One defines a  $W^v$ -invariant relation  $\leq$  on  $\mathbb{A}$  by:  $x \leq y \Leftrightarrow y - x \in \mathcal{T}$ .

Let  $x, y \in \mathbb{A}$  be such that  $x \neq y$ . The ray with the base point  $x$  and containing  $y$  (or the intervals  $(x, y]$ ,  $(x, y)$ , ...) is called *preordered* if  $x \leq y$  or  $y \leq x$  and *generic* if  $y - x \in \pm \mathring{\mathcal{T}}$ , the interior of  $\pm \mathcal{T}$ .

## 2.3 Metric properties of $W^v$

In this subsection we prove that when  $W^v$  is infinite there do not exist a  $W^v$ -invariant norm on  $\mathbb{A}$  and we also establish a density property of the walls of  $\mathbb{A}$ .

Two true walls  $M_1$  and  $M_2$  are said to be *consecutive* if they are of the form  $\alpha^{-1}(\{k\})$ ,  $\alpha^{-1}(\{k \pm 1\})$  for some  $\alpha \in \Phi$  and some  $k \in \mathbb{Z}$ .

**Proposition 2.1.** *1. Suppose that there exists a  $W^v$ -invariant norm on  $\mathbb{A}$ . Then  $W^v$  is finite.*

*2. Let  $|\cdot|$  be a norm on  $\mathbb{A}$ ,  $d$  be the induced distance on  $\mathbb{A}$  and suppose that  $W^v$  is infinite. Then for every  $\epsilon > 0$  there exists a vectorial wall  $M_0$  such that for all consecutive true walls  $M_1$  and  $M_2$  of the direction  $M_0$ ,  $d(M_1, M_2) < \epsilon$ .*

*Proof.* Let  $B \subset Y^{\dim \mathbb{A}}$  be a  $\mathbb{Z}$ -basis of  $Y$ . Then the map  $W^v \rightarrow Y^{\dim \mathbb{A}}$  sending each  $w$  on  $w.B$  is injective. Thus if  $W^v$  is infinite,  $\{w.B \mid w \in W^v\}$  is not bounded. Point 1 follows.

Suppose that  $W^v$  is infinite. Let  $(\beta_n) \in \Phi_+^{\mathbb{N}}$  be an injective sequence. Let  $\epsilon > 0$  and  $u \in C_f^v$  be such that  $|u| < \epsilon$ . For  $n \in \mathbb{N}$ , write  $\beta_n = \sum_{i \in I} \lambda_{i,n} \alpha_i$ , with  $\lambda_{i,n} \in \mathbb{N}$  for all  $(i, n) \in I \times \mathbb{N}$ . One has

$$\beta_n(u) = \sum_{i \in I} \lambda_{i,n} \alpha_i(u) \geq \left( \min_{i \in I} \alpha_i(u) \right) \sum_{i \in I} \lambda_{i,n} \rightarrow +\infty.$$

Let  $n \in \mathbb{N}$  be such that  $\beta_n(u) \geq 1$  and  $M_0 = \beta_n^{-1}(\{0\})$ . Then for all consecutive true walls  $M_1$  and  $M_2$  of the direction  $M_0$ ,  $d(M_1, M_2) < \epsilon$ , which proves the proposition.  $\square$

## 2.4 Filters and enclosure

### Filters

A filter on a set  $\mathcal{E}$  is a nonempty set  $F$  of nonempty subsets of  $\mathcal{E}$  such that, for all subsets  $E, E'$  of  $\mathcal{E}$ , if  $E, E' \in F$  then  $E \cap E' \in F$  and, if  $E' \subset E$ , with  $E' \in F$  then  $E \in F$ .

If  $\mathcal{E}$  is a set and  $F, F'$  are filters on  $\mathcal{E}$ ,  $F \cup F'$  is the filter  $\{E \cup E' \mid (E, E') \in F \times F'\}$ .

If  $F$  is a filter on a set  $\mathcal{E}$ , and  $E'$  is a subset of  $\mathcal{E}$ , one says that  $F$  contains  $E'$  if every element of  $F$  contains  $E'$ . If  $E'$  is nonempty, the set  $F_{E'}$  of subsets of  $E$  containing  $E'$  is a filter. By abuse of language, we will sometimes say that  $E'$  is a filter by identifying  $F_{E'}$  and  $E'$ . A filter  $F$  is said to be contained in another filter  $F'$ :  $F \subset F'$  (resp. in a subset  $Z$  in  $\mathcal{E}$ :  $F \subset Z$ ) if and only if any set in  $F'$  (resp. if  $Z$ ) is in  $F$ . If  $F$  is a filter on a finite-dimensional real-affine space  $\mathcal{E}$ , its closure  $\overline{F}$  (resp. its convex hull) is the filter of subsets of  $\mathcal{E}$  containing the closure (resp. the convex hull) of some element of  $F$ . The *support* of a filter  $F$  on  $\mathcal{E}$  is the minimal affine space containing  $F$ .

## Enclosure of a filter

Let  $\Delta$  be the set of all roots of the root generating system  $\mathcal{S}$  defined in Chapter 1 of [Kac94]. We only recall that  $\Delta \subset \mathbb{A}^*$  and that  $\Delta \cap \mathbb{R}\Phi = \Phi$ .

Let  $E$  be a filter on  $\mathbb{A}$ . The enclosure  $\text{cl}(E)$  is the filter on  $\mathbb{A}$  defined as follows. A set  $E'$  is in  $\text{cl}(E)$  if there exists  $(k_\alpha) \in (\mathbb{Z} \cup \{+\infty\})^\Delta$  satisfying:

$$E' \supset \bigcap_{\alpha \in \Delta} D(\alpha, k_\alpha) \supset E.$$

In the reductive case, i.e when  $\mathcal{S}$  is associated to a Cartan matrix or equivalently when  $\Phi$  is finite,  $\Delta = \Phi$  and the enclosure of a set  $E$  is simply the intersection of the true half-apartments containing  $E$ .

## 2.5 Face, sector-faces, chimneys and germs

### Sector-faces, sectors

A *sector-face*  $f$  of  $\mathbb{A}$  is a set of the form  $x + F^v$  for some vectorial face  $F^v$  and some  $x \in \mathbb{A}$ . The point  $x$  is its *base point* and  $F^v$  is its *direction*. The *germ at infinity*  $\mathfrak{F} = \text{germ}_\infty(f)$  of  $f$  is the filter composed of all the subsets of  $\mathbb{A}$  which contain an element of the form  $x + u + F^v$ , for some  $u \in \overline{F^v}$ . In this paper, we will mainly consider germs at infinity of sector-faces (and not their germs at their base points) and thus we will sometimes say “germ” instead of “germ at infinity”.

When  $F^v$  is a vectorial chamber, one calls  $f$  a *sector*. The intersection of two sectors of the same direction is a sector of the same direction. A *sector-germ* of  $\mathbb{A}$  is a filter which is the germ at infinity of some sector of  $\mathbb{A}$ . We denote by  $\pm\infty$  the germ of  $\pm C_f^v$ .

The sector-face  $f$  is said to be *spherical* if  $F^v \cap \pm\mathcal{T}$  is nonempty. A *sector-panel* is a sector-face contained in a wall and spanning it as an affine space. Sectors and sector-panels are spherical.

### Faces

Let  $x \in \mathbb{A}$  and let  $F^v$  be a vectorial face of  $\mathbb{A}$ . The *face*  $F(x, F^v)$  is the filter defined as follows: a set  $E \subset \mathbb{A}$  is an element of  $F(x, F^v)$  if, and only if, there exist  $(k_\alpha), (k'_\alpha) \in (\mathbb{Z} \cup \{+\infty\})^\Delta$  and a neighborhood  $\Omega$  of  $x$  in  $\mathbb{A}$  such that  $E \supset \bigcap_{\alpha \in \Delta} (D(\alpha, k_\alpha) \cap D^\circ(\alpha, k'_\alpha)) \supset \Omega \cap (x + F^v)$ . A *face* of  $\mathbb{A}$  is a filter  $F$  that can be written  $F = F(x, F^v)$ , for some  $x \in \mathbb{A}$  and some vectorial face  $F^v$ .

A *chamber* is a face whose support is  $\mathbb{A}$ . A *panel* is a face whose support is a wall.

In the reductive case (i.e when  $\Phi$  is finite), we obtain the usual notion of faces.

## Chimneys

Let  $F$  be a face of  $\mathbb{A}$  and  $F^v$  be a vectorial face of  $\mathbb{A}$ . The *chimney*  $\mathfrak{r}(F, F^v)$  is the filter  $\text{cl}(F + F^v)$ . A *chimney*  $\mathfrak{r}$  is a filter on  $\mathbb{A}$  of the form  $\mathfrak{r} = \mathfrak{r}(F, F^v)$  for some face  $F$  and some vectorial face  $F^v$ . The enclosure of a sector-face is thus a chimney. The vectorial face  $F^v$  is uniquely determined by  $\mathfrak{r}$  (this is not necessarily the case of the face  $F$ ) and one calls it the *direction* of  $\mathfrak{r}$ .

Let  $\mathfrak{r}$  be a chimney and  $F^v$  be its direction. One says that  $\mathfrak{r}$  is *splayed* if  $F^v$  is spherical (or equivalently if  $F^v$  contains a generic ray, see Subsection 2.2). One says that  $\mathfrak{r}$  is *solid* if the fixer in  $W^v$  of the direction of the support of  $\mathfrak{r}$  is finite. A splayed chimney is solid.

Let  $\mathfrak{r} = \mathfrak{r}(F, F^v)$  be a chimney. A shortening of  $\mathfrak{r}$  is a chimney of the form  $\mathfrak{r}(F + u, F^v)$ , for some  $u \in \overline{F^v}$ . The *germ (at infinity)*  $\mathfrak{R} = \text{germ}_\infty(\mathfrak{r})$  of  $\mathfrak{r}$  is the filter composed of all subsets of  $\mathbb{A}$  which contain a shortening of  $\mathfrak{r}$ . A sector-germ is an example of a germ of a splayed chimney.

## 2.6 Measure

Let  $\alpha \in \Phi$ . Write  $\alpha = w.\alpha_i$  for some  $i \in I$  and  $w \in W^v$ . Then  $w.\alpha_i^\vee$  does not depend on the choice of  $w$  and one denotes it  $\alpha^\vee$ . An *automorphism* of  $\mathbb{A}$  is an affine bijection  $\phi : \mathbb{A} \rightarrow \mathbb{A}$  stabilizing the set  $\{(M(\alpha, k), \alpha^\vee) | (\alpha, k) \in \Phi \times \mathbb{Z}\}$ . One has  $W^a \subset W^v \ltimes Y \subset \text{Aut}(\mathbb{A})$ , where  $\text{Aut}(\mathbb{A})$  is the group of automorphisms of  $\mathbb{A}$ .

An apartment of type  $\mathbb{A}$  is a set  $A$  with a nonempty set  $\text{Isom}^w(\mathbb{A}, A)$  of bijections (called Weyl isomorphisms) such that if  $f_0 \in \text{Isom}^w(\mathbb{A}, A)$  then  $f \in \text{Isom}^w(\mathbb{A}, A)$  if and only if, there exists  $w \in W^a$  satisfying  $f = f_0 \circ w$ . An isomorphism (resp. a Weyl isomorphism, a vectorially Weyl isomorphism) between two apartments  $\phi : A \rightarrow A'$  is a bijection such that for any  $f \in \text{Isom}^w(\mathbb{A}, A)$  and  $f' \in \text{Isom}^w(\mathbb{A}, A')$ , one has  $f' \circ \phi \circ f^{-1} \in \text{Aut}(\mathbb{A})$  (resp.  $f' \circ \phi \circ f^{-1} \in W^a$ ,  $f' \circ \phi \circ f^{-1} \in (W^v \ltimes \mathbb{A}) \cap \text{Aut}(\mathbb{A})$ ).

Each apartment  $A$  of type  $\mathbb{A}$  can be equipped with the structure of an affine space by using an isomorphism of apartments  $\phi : \mathbb{A} \rightarrow A$ . We equip each apartment with its topology defined by its structure of a finite-dimensional real-affine space.

We extend all the notions that are preserved by  $\text{Aut}(\mathbb{A})$  to each apartment. In particular, enclosure, sector-faces, faces, chimneys, germs of chimneys, ... are well defined in any apartment of type  $\mathbb{A}$ . If  $A$  is an apartment of type  $\mathbb{A}$  and  $x, y \in A$ , then we denote by  $[x, y]_A$  the closed segment of  $A$  between  $x$  and  $y$ .

We say that an apartment contains a filter if it contains at least one element of this filter. We say that a map fixes a filter if it fixes at least one element of this filter.

**Definition 2.2.** A *measure of type  $\mathbb{A}$*  is a set  $\mathcal{I}$  endowed with a covering  $\mathcal{A}$  of subsets called *apartments* such that:

(MA1) Any  $A \in \mathcal{A}$  admits a structure of an apartment of type  $\mathbb{A}$ .

(MA2) If  $F$  is a point, a germ of a preordered interval, a generic ray or a solid chimney in an apartment  $A$  and if  $A'$  is another apartment containing  $F$ , then  $A \cap A'$  contains the enclosure  $\text{cl}_A(F)$  of  $F$  and there exists a Weyl isomorphism from  $A$  onto  $A'$  fixing  $\text{cl}_A(F)$ .

(MA3) If  $\mathfrak{R}$  is the germ of a splayed chimney and if  $F$  is a face or a germ of a solid chimney, then there exists an apartment that contains  $\mathfrak{R}$  and  $F$ .

(MA4) If two apartments  $A, A'$  contain  $\mathfrak{R}$  and  $F$  as in (MA3), then there exists a Weyl isomorphism from  $A$  to  $A'$  fixing  $\text{cl}_A(\mathfrak{R} \cup F)$ .

(MAO) If  $x, y$  are two points contained in two apartments  $A$  and  $A'$ , and if  $x \leq_A y$  then the two segments  $[x, y]_A$  and  $[x, y]_{A'}$  are equal.



We assume that there exists a group  $G$  acting strongly transitively on  $\mathcal{I}$ , which means that:

- $G$  acts on  $\mathcal{I}$ ,
- $g.A$  is an apartment for every  $g \in G$  and every apartment  $A$ ,
- for every  $g \in G$  and every apartment  $A$ , the map  $A \rightarrow g.A$  is an isomorphism of apartments,
- all isomorphisms involved in the above axioms are induced by elements of  $G$ .

We choose in  $\mathcal{I}$  a “fundamental” apartment, that we identify with  $\mathbb{A}$ . As  $G$  acts strongly transitively on  $\mathcal{I}$ , the apartments of  $\mathcal{I}$  are the sets  $g.A$  for  $g \in G$ . The stabilizer  $N$  of  $\mathbb{A}$  induces a group  $\nu(N)$  of affine automorphisms of  $\mathbb{A}$  and we assume that  $\nu(N) = W^v \ltimes Y$ .

All the isomorphisms that we will consider in this paper will be vectorially Weyl isomorphisms and we will say “isomorphism” instead of “vectorially Weyl isomorphism”.

We suppose that  $\mathcal{I}$  is thick of finite thickness, which means that for each panel  $P$ , the number of chambers whose closure contains  $P$  is finite and greater than 2. This definition coincides with the usual one when  $\mathcal{I}$  is a building.

An example of such a measure  $\mathcal{I}$  is the measure associated to a split Kac-Moody group over a field equipped with a nonarchimedean discrete valuation constructed in [GR08] and in [Rou16].

A measure  $\mathcal{I}$  is a building if and only if  $W^v$  is finite, see [Rou11] 2.2 6).

## 2.7 Retractions centered at sector-germs

If  $A$  and  $B$  are two apartments, and  $\phi : A \rightarrow B$  is an isomorphism of apartments fixing some filter  $\mathcal{X}$ , one writes  $\phi : A \xrightarrow{\mathcal{X}} B$ . If  $A$  and  $B$  share a sector-germ  $\mathfrak{s}$ , there exists a unique isomorphism of apartments  $\phi : A \rightarrow B$  fixing  $A \cap B$ . Indeed, by (MA4), there exists an isomorphism  $\psi : A \rightarrow B$  fixing  $\mathfrak{s}$ . Let  $x \in A \cap B$ . By (MA4),  $A \cap B$  contains the convex hull  $\text{Conv}(x, \mathfrak{s})$  in  $A$  of  $x$  and  $\mathfrak{s}$  and there exists an isomorphism of apartments  $\psi' : A \rightarrow B$  fixing  $\text{Conv}(x, \mathfrak{s})$ . Then  $\psi'^{-1} \circ \psi : A \rightarrow A$  is an isomorphism of affine spaces fixing  $\mathfrak{s}$ :  $\psi' = \psi$ . By definition  $\psi'(x) = x$  and thus  $\psi$  fixes  $A \cap B$ . The uniqueness is a consequence of the fact that the only affine morphism fixing some nonempty open set of  $A$  is the identity. One denotes by  $A \xrightarrow{A \cap B} B$  or by  $A \xrightarrow{\mathfrak{s}} B$  the unique isomorphism of apartments from  $A$  to  $B$  fixing  $\mathfrak{s}$ .

Fix a sector-germ  $\mathfrak{s}$  of  $\mathcal{I}$  and an apartment  $A$  containing  $\mathfrak{s}$ . Let  $x \in \mathcal{I}$ . By (MA3), there exists an apartment  $A_x$  of  $\mathcal{I}$  containing  $x$  and  $\mathfrak{s}$ . Let  $\phi : A_x \xrightarrow{\mathfrak{s}} A$  fixing  $\mathfrak{s}$ . By [Rou11] 2.6,  $\phi(x)$  does not depend on the choices we made and thus we can let  $\rho_{A, \mathfrak{s}}(x) = \phi(x)$ .

The map  $\rho_{A, \mathfrak{s}}$  is a retraction from  $\mathcal{I}$  onto  $A$ . It only depends on  $\mathfrak{s}$  and  $A$  and we call it the *retraction onto  $A$  centered at  $\mathfrak{s}$* . We denote by  $\mathcal{I} \xrightarrow{\mathfrak{s}} A$  the retraction onto  $A$  fixing  $\mathfrak{s}$ . We denote by  $\rho_{\pm\infty}$  the retraction onto  $\mathbb{A}$  centered at  $\pm\infty$ .

## 2.8 Parallelism in $\mathcal{I}$

Let us explain briefly the notion of parallelism in  $\mathcal{I}$ . This is done in detail in [Rou11] Section 3.

Let us begin with rays. Let  $\delta$  and  $\delta'$  be two generic rays in  $\mathcal{I}$ . By (MA3) and [Rou11] 2.2 3) there exists an apartment  $A$  containing sub-rays of  $\delta$  and  $\delta'$  and we say that  $\delta$  and  $\delta'$

are *parallel*, if these sub-rays are parallel in  $A$ . Parallelism is an equivalence relation. The parallelism class of a generic ray  $\delta$  is denoted  $\delta_\infty$  and is called its *direction*.

We now review the notion of parallelism for sector-faces. We refer to [Rou11], 3.3.4)) for the details.

### Twin-building $\mathcal{I}^\infty$ at infinity

If  $f$  and  $f'$  are two spherical sector-faces, there exists an apartment  $B$  containing their germs  $\mathfrak{F}$  and  $\mathfrak{F}'$ . One says that  $f$  and  $f'$  are parallel if  $\mathfrak{F} = \text{germ}_\infty(x + F^v)$  and  $\mathfrak{F}' = \text{germ}_\infty(y + F'^v)$  for some  $x, y \in B$  and for some vectorial face  $F^v$  of  $B$ . Parallelism is an equivalence relation. The parallelism class of a sector-face germ  $\mathfrak{F}$  is denoted  $\mathfrak{F}_\infty$  and is called its *direction*. We denote by  $\mathcal{I}^\infty$  the set of directions of spherical faces of  $\mathcal{I}$ . If  $\mathfrak{s}$  is a sector, all the sectors having the germ  $\mathfrak{s}$  have the same direction. We denote it  $\mathfrak{s}$  by abuse of notation. If  $M$  is a wall of  $\mathcal{I}$ , its direction  $M^\infty \subset \mathcal{I}^\infty$  is defined to be the set of germs at infinity  $\mathfrak{F}_\infty$  such that  $\mathfrak{F} = \text{germ}_\infty(f)$ , with  $f$  a spherical sector-face contained in  $M$ .

Let  $\mathfrak{F}_\infty \in \mathcal{I}^\infty$  and  $A$  be an apartment. One says that  $A$  contains  $\mathfrak{F}_\infty$  if  $A$  contains some sector-face  $f$  whose direction is  $\mathfrak{F}_\infty$ .

- Proposition 2.3.** 1. Let  $x \in \mathcal{I}$  and  $\mathfrak{F}_\infty \in \mathcal{I}^\infty$  (resp.  $\delta_\infty$  be a generic ray direction). Then there exists a unique sector-face  $x + \mathfrak{F}_\infty$  (resp.  $x + \delta_\infty$ ) based at  $x$  and whose direction is  $\mathfrak{F}_\infty$  (resp.  $\delta_\infty$ ).
2. Let  $A_x$  be an apartment containing  $x$  and  $\mathfrak{F}_\infty$  (resp.  $\delta_\infty$ ) (which exists by (MA3)). Let  $f$  (resp.  $\delta'$ ) be a sector-face (resp. a generic ray) of  $A_x$  whose direction is  $\mathfrak{F}_\infty$  (resp.  $\delta_\infty$ ). Then  $x + \mathfrak{F}_\infty$  (resp.  $x + \delta_\infty$ ) is the sector-face (resp. generic ray) of  $A_x$  parallel to  $f$  (resp.  $\delta'$ ) and based at  $x$ .
3. Let  $B$  be an apartment containing  $\mathfrak{F}_\infty$  (resp.  $\delta_\infty$ ). Then for all  $x \in B$ ,  $x + \mathfrak{F}_\infty \subset B$  (resp.  $x + \delta_\infty \subset B$ ).

*Proof.* The points 1 and 2 for sector-faces are Proposition 4.7.1) of [Rou11] and its proof. Point 3 is a consequence of 2. The statement for rays is analogous (see Lemma 3.2 of [Héb17]).  $\square$

Let  $f, f'$  be sector-faces. One says that  $f$  dominates  $f'$  (resp.  $f$  and  $f'$  are opposite) if  $\text{germ}_\infty(f) = \text{germ}_\infty(x + F^v)$ ,  $\text{germ}_\infty(f') = \text{germ}_\infty(x' + F'^v)$  for some  $x, x' \in \mathcal{I}$  and  $F^v, F'^v$  two vectorial faces of a same apartment of  $\mathcal{I}$  such that  $\overline{F^v} \supset F'^v$  (resp. such that  $F'^v = -F^v$ ). By Proposition 3.2 2) and 3) of [Rou11], these notions extend to  $\mathcal{I}^\infty$ .

## 3 Splitting of apartments

### 3.1 Splitting of apartments in two half-apartments

The aim of this section is to show that if  $A$  is an apartment,  $M$  is a wall of  $A$ ,  $\mathfrak{F}$  is a sector-panel of  $M^\infty$  and  $\mathfrak{s}$  is a sector-germ dominating  $\mathfrak{F}_\infty$ , then there exist two opposite half-apartments  $D_1$  and  $D_2$  of  $A$  such that their wall is parallel to  $M$  and such that for both  $i \in \{1, 2\}$ ,  $D_i$  and  $\mathfrak{s}$  are contained in some apartment. This is Lemma 3.6. This property is called “sundial configuration” in Section 2 of [BS14]. This section will enable us to show that for each choice of sign, the distances of positive types and of negative types are equivalent.

For simplicity, we assume that  $\Phi$  is reduced. This assumption can be dropped with minor changes to the next lemma.

**Lemma 3.1.** *Let  $\alpha \in \Phi$  and  $k \in \mathbb{R}$ . Then  $\text{cl}(D(\alpha, k)) = D(\alpha, \lceil k \rceil)$ .*

*Proof.* By definition of  $\text{cl}$ ,  $D(\alpha, \lceil k \rceil) \in \text{cl}(D(\alpha, k))$  and hence  $\text{cl}(D(\alpha, k)) \subset D(\alpha, \lceil k \rceil)$ .

Let  $E \in \text{cl}(D(\alpha, k))$ . By definition, there exists  $(k_\beta) \in (\mathbb{Z} \cup \infty)^\Delta$  such that  $E \supset \bigcap_{\beta \in \Delta} D(\beta, k_\beta) \supset D(\alpha, k)$ . Let  $\beta \in \Delta \setminus \{\alpha\}$ . As  $\beta \notin \mathbb{R}_+ \alpha$ ,  $D(\beta, \ell) \not\supset D(\alpha, k)$  for all  $\ell \in \mathbb{Z}$ . Hence  $k_\beta = +\infty$ .

As the family  $(D(\alpha, \ell))_{\ell \in \mathbb{R}}$  is increasing for the inclusion,  $k_\alpha \geq \lceil k \rceil$ .

Therefore  $\bigcap_{\beta \in \Delta} D(\beta, k_\beta) = D(\alpha, k_\alpha) \supset D(\alpha, \lceil k \rceil)$ . Consequently,  $D(\alpha, \lceil k \rceil) \subset \text{cl}(D(\alpha, k))$  and thus  $\text{cl}(D(\alpha, k)) = D(\alpha, \lceil k \rceil)$ .  $\square$

**Lemma 3.2.** *Let  $A, B$  be two distinct apartments of  $\mathcal{I}$  containing a half-apartment  $D$ . Then  $A \cap B$  is a true half-apartment.*

*Proof.* Using isomorphisms of apartments, we may assume  $A = \mathbb{A}$ . Let  $\alpha \in \Phi$  and  $k \in \mathbb{R}$  be such that  $D = D(\alpha, k)$ . Set  $M_0 = \alpha^{-1}(\{0\})$ . Let  $S$  be a sector of  $\mathbb{A}$  based at 0 and dominating some sector-panel  $f \subset M_0$ . Let  $f' = -f$  and  $\mathfrak{s}$ ,  $\mathfrak{F}_\infty$  and  $\mathfrak{F}'_\infty$  be the directions of  $S$ ,  $f$  and  $f'$ . Let  $x \in \mathbb{A} \cap B$ . Then by Proposition 2.3 (3),  $\mathbb{A} \cap B \supset x + \mathfrak{s} \cup x + \mathfrak{F}'_\infty$ . As  $\text{germ}_\infty(x + \mathfrak{s})$ ,  $\text{germ}_\infty(x + \mathfrak{F}'_\infty)$  are the germs of splayed chimneys, we can apply (MA4) and we get that  $\mathbb{A} \cap B \supset \text{cl}(\text{germ}_\infty(x + \mathfrak{s}) \cup \text{germ}_\infty(x + \mathfrak{F}'_\infty))$ . But

$$\text{cl}(\text{germ}_\infty(x + \mathfrak{s}) \cup \text{germ}_\infty(x + \mathfrak{F}'_\infty)) = \text{cl}\left(\overline{\text{Conv}}(\text{germ}_\infty(x + \mathfrak{s}), \text{germ}_\infty(x + \mathfrak{F}'_\infty))\right),$$

where  $\overline{\text{Conv}}$  denotes the closure of the convex hull. Therefore

$$\text{cl}(\text{germ}_\infty(x + \mathfrak{s}) \cup \text{germ}_\infty(x + \mathfrak{F}'_\infty)) = \text{cl}(D(\alpha, -\alpha(x))) = D(\alpha, \lceil -\alpha(x) \rceil)$$

(by Lemma 3.1). Thus  $\mathbb{A} \cap B \supset D(\alpha, \lceil -\alpha(x) \rceil) \ni x$ . Consequently,

$$\mathbb{A} \cap B \supset \bigcup_{x \in \mathbb{A} \cap B} D(\alpha, \lceil -\alpha(x) \rceil) \supset \mathbb{A} \cap B.$$

Hence  $\mathbb{A} \cap B = D(\alpha, \ell)$ , where  $\ell = \max_{x \in \mathbb{A} \cap B} \lceil -\alpha(x) \rceil \in \mathbb{Z}$ , and the lemma follows.  $\square$

From now on, unless otherwise stated, “half-apartment” (resp. “wall”) will implicitly refer to “true half-apartment” (resp. “true wall”).

**Lemma 3.3.** *Let  $M$  be a wall of  $\mathbb{A}$  and  $w \in W^v \ltimes Y$  be an element fixing  $M$ . Then  $w \in \{\text{Id}, s\}$ , where  $s$  is the reflection of  $W^v \ltimes Y$  with respect to  $M$ .*

*Proof.* One writes  $w = \tau \circ u$ , with  $u \in W^v$  and  $\tau$  a translation of  $\mathbb{A}$ . Then  $u(M)$  is a wall parallel to  $M$ . Let  $M_0$  be the wall parallel to  $M$  containing 0. Then  $u(M_0)$  is a wall parallel to  $M_0$  and containing 0:  $u(M_0) = M_0$ . Let  $C$  be a vectorial chamber adjacent to  $M_0$ . Then  $u(C)$  is a chamber adjacent to  $C$ :  $u(C) \in \{C, s_0(C)\}$ , where  $s_0$  is the reflection of  $W^v$  with respect to  $M_0$ . After composing  $u$  with  $s_0$ , we may assume that  $u(C) = C$  and thus  $u = \text{Id}$  (because the action of  $W^v$  on the set of chambers is simply transitive).  $\square$

If  $A$  is an apartment and  $D, D'$  are half-apartments of  $A$ , we say that  $D$  and  $D'$  are opposite if  $D \cap D'$  is a wall and one says that  $D$  and  $D'$  have opposite directions if their walls are parallel and  $D \cap D'$  is not a half-apartment.

**Lemma 3.4.** *Let  $A_1, A_2, A_3$  be distinct apartments. Suppose that  $A_1 \cap A_2$ ,  $A_1 \cap A_3$  and  $A_2 \cap A_3$  are half-apartments such that  $A_1 \cap A_3$  and  $A_2 \cap A_3$  have opposite directions. Let  $M$  be the wall of  $A_1 \cap A_3$ .*

1. One has  $A_1 \cap A_2 \cap A_3 = M$  where  $M$  is the wall of  $A_1 \cap A_3$ , and for all  $(i, j, k) \in \{1, 2, 3\}^3$  such that  $\{i, j, k\} = \{1, 2, 3\}$ ,  $A_i \cap A_j$  and  $A_i \cap A_k$  are opposite.
2. Let  $s : A_3 \rightarrow A_3$  be the reflection with respect to  $M$ ,  $\phi_1 : A_3 \xrightarrow{A_1 \cap A_3} A_1$ ,  $\phi_2 : A_3 \xrightarrow{A_2 \cap A_3} A_2$  and  $\phi_3 : A_2 \xrightarrow{A_1 \cap A_2} A_1$ . Then the following diagram is commutative:

$$\begin{array}{ccc} A_3 & \xrightarrow{s} & A_3 \\ \downarrow \phi_2 & & \downarrow \phi_1 \\ A_2 & \xrightarrow{\phi_3} & A_1 \end{array}$$

*Proof.* Point 1 is a consequence of “Propriété du Y” and of its proof (Section 4.9 of [Rou11]).

Let  $\phi = \phi_1^{-1} \circ \phi_3 \circ \phi_2 : A_3 \rightarrow A_3$ . Then  $\phi$  fixes  $M$ . Let  $D_1 = A_2 \cap A_3$ ,  $D_2 = A_1 \cap A_3$  and  $D_3 = A_1 \cap A_2$ . One has  $\phi_3(A_2) = A_1 = D_2 \cup D_3$  and thus  $\phi_3(D_1) = D_2$ . One has  $\phi_1^{-1}(D_2) = D_2$ . Thus  $\phi(D_1) = D_2$ . We conclude with Lemma 3.3.  $\square$

**Lemma 3.5.** *Let  $\mathfrak{s}, \mathfrak{s}'$  be two opposite sector-germs of  $\mathcal{I}$ . Then there exists a unique apartment containing  $\mathfrak{s}$  and  $\mathfrak{s}'$ .*

*Proof.* The existence is a particular case of (MA3). Let  $A$  and  $A'$  be apartments containing  $\mathfrak{s} \cup \mathfrak{s}'$ . Let  $x \in A \cap A'$ . Then by Proposition 2.3 (3),  $A = \bigcup_{y \in x + \mathfrak{s}} y + \mathfrak{s}' \subset A \cap A'$ , thus  $A \subset A'$  and the lemma follows by symmetry.  $\square$

Recall the definition of  $\mathcal{I}^\infty$  and of the direction  $M^\infty$  of a wall  $M$  from Subsection 2.8. The following lemma is similar to Proposition 2.9.1) of [Rou11]. This is analogous to the *sundial configuration* of Section 2 of [BS14].

**Lemma 3.6.** *Let  $A$  be an apartment,  $M$  be a wall of  $A$  and  $M^\infty$  be its direction. Let  $\mathfrak{F}_\infty$  be the direction of a sector-panel of  $M^\infty$  and  $\mathfrak{s}$  be a sector-germ dominating  $\mathfrak{F}_\infty$  and not contained in  $A$ . Then there exists a unique pair  $\{D_1, D_2\}$  of half-apartments of  $A$  such that:*

- $D_1$  and  $D_2$  are opposite with the common wall  $M'$  parallel to  $M$
- for all  $i \in \{1, 2\}$ ,  $D_i$  and  $\mathfrak{s}$  are in some apartment  $A_i$ .

*Moreover:*

- $D_1$  and  $D_2$  are true half-apartments
- such apartments  $A_1$  and  $A_2$  are unique and if  $D$  is the half-apartment of  $A_1$  opposite to  $D_1$ , then  $D \cap D_2 = D_1 \cap D_2 = M'$  and  $A_2 = D_2 \cup D$ .

*Proof.* Let us first show the existence of  $D_1$  and  $D_2$ . Let  $\mathfrak{F}'_\infty$  be the sector-panel of  $M^\infty$  opposite to  $\mathfrak{F}_\infty$ . Let  $\mathfrak{s}'_1$  and  $\mathfrak{s}'_2$  be the sector-germs of  $A$  containing  $\mathfrak{F}'_\infty$ . For  $i \in \{1, 2\}$ , let  $A_i$  be an apartment of  $\mathcal{I}$  containing  $\mathfrak{s}'_i$  and  $\mathfrak{s}$ , which exists by (MA3). Let  $i \in \{1, 2\}$  and  $x \in A \cap A_i$ . Then by Proposition 2.3 (3),  $x + \mathfrak{s}'_i \subset A \cap A_i$  and the open half-apartment  $E_i = \bigcup_{y \in x + \mathfrak{s}'_i} y + \mathfrak{F}_\infty \subset A \cap A_i$  is contained in  $A$  and  $A_i$ .

Suppose  $A_1 = A_2$ . Then  $A_1 \supset \bigcup_{x \in E_1} x + \mathfrak{s}'_2 = A$  and thus  $A_1 = A \supset \mathfrak{s}$ . This is absurd and thus  $A_1 \neq A_2$ .

The apartments  $A_1, A_2$  contain  $\mathfrak{F}'_\infty$  and  $\mathfrak{s}$ . Take  $x \in A_1 \cap A_2$ . Then by Proposition 2.3 (3),  $A_1 \cap A_2$  contains the open half-apartment  $\bigcup_{y \in x + \mathfrak{s}} y + \mathfrak{F}'_\infty$ . By Lemma 3.2,  $A_1 \cap A_2$  is a half-apartment. Thus we can apply Lemma 3.4:  $A_1 \cap A_2 \cap A = M'$ , where  $M'$  is a wall of  $A$

parallel to  $M$ . Set  $D_i = A \cap A_i$  for all  $i \in \{1, 2\}$ . Then  $\{D_1, D_2\}$  fulfills the requirements of the lemma.

Let  $D'_1, D'_2$  be another pair of opposite half-apartments of  $A$  such that for all  $i \in \{1, 2\}$ ,  $D'_i$  and  $\mathfrak{s}$  are contained in some apartment  $A'_i$  and such that  $D'_1 \cap D'_2$  is parallel to  $M$ .

We can assume  $D'_i \supset \mathfrak{s}'_i$  for both  $i \in \{1, 2\}$ . Let  $\mathfrak{s}'$  be the sector-germ of  $A'_i$  opposite to  $\mathfrak{s}$ . Then  $\mathfrak{s}'$  dominates  $\mathfrak{F}'_\infty$  and is included in  $D'_i$ . Therefore  $\mathfrak{s}' = \mathfrak{s}_i$ . By Lemma 3.5,  $A'_i = A_i$ , which proves the uniqueness of  $\{D_1, D_2\}$  and  $\{A_1, A_2\}$ .

Moreover, by Proposition 2.9 2) of [Rou11],  $D \cup D_2$  is an apartment. As  $D \cup D_2 \supset \mathfrak{s} \cup \mathfrak{s}_2$ , one has  $D \cup D_2 = A_2$ , which concludes the proof of the lemma.  $\square$

## 3.2 Splitting of apartments

In this subsection we mainly generalize Lemma 3.6. We show that if  $\mathfrak{s}$  is a sector-germ of  $\mathcal{I}$  and if  $A$  is an apartment of  $\mathcal{I}$ , then  $A$  is the union of a finite number of convex closed subsets  $P_i$  of  $A$  such that for all  $i$ ,  $P_i$  and  $\mathfrak{s}$  are contained in some apartment. This is Proposition 3.7.

Let  $\mathfrak{s}, \mathfrak{s}'$  be two sector-germs of the same sign. Let  $A$  be an apartment containing  $\mathfrak{s}$  and  $\mathfrak{s}'$ , which exists by (MA3). Let  $d(\mathfrak{s}, \mathfrak{s}')$  be the length of a minimal gallery from  $\mathfrak{s}$  to  $\mathfrak{s}'$  (we use the fact that  $W^v$  is a Coxeter group). By (MA4),  $d(\mathfrak{s}, \mathfrak{s}')$  does not depend on the choice of  $A$ .

Let  $\mathfrak{s}$  be a sector-germ and  $A$  be an apartment of  $\mathcal{I}$ . Let  $d_{\mathfrak{s}}(A)$  be the minimum of the  $d(\mathfrak{s}, \mathfrak{s}')$ , where  $\mathfrak{s}'$  runs over the sector-germs of  $A$  of the same sign as  $\mathfrak{s}$ . Let  $\mathcal{D}_A$  be the set of half-apartments of  $A$ . One sets  $\mathcal{P}_{A,0} = \{A\}$  and for all  $n \in \mathbb{N}^*$ ,  $\mathcal{P}_{A,n} = \{\bigcap_{i=1}^n D_i \mid (D_i) \in (\mathcal{D}_A)^n\}$ . The following proposition is very similar to Proposition 4.3.1 of [Cha10].

**Proposition 3.7.** *Let  $A$  be an apartment of  $\mathcal{I}$ ,  $\mathfrak{s}$  be a sector-germ of  $\mathcal{I}$  et  $n = d_{\mathfrak{s}}(A)$ . Then there exist  $P_1, \dots, P_k \in \mathcal{P}_{A,n}$ , with  $k \leq 2^n$  such that  $A = \bigcup_{i=1}^k P_i$  and for each  $i \in \llbracket 1, k \rrbracket$ ,  $P_i$  and  $\mathfrak{s}$  are contained in some apartment  $A_i$  such that there exists an isomorphism  $f_i : A_i \xrightarrow{P_i} A$ .*

*Proof.* We do it by induction on  $n$ . This is clear if  $n = 0$ . Let  $n \in \mathbb{N}_{>0}$ . Suppose this is true for every apartment  $B$  such that  $d_{\mathfrak{s}}(B) \leq n - 1$ .

Let  $B$  be an apartment such that  $d_{\mathfrak{s}}(B) = n$ . Let  $\mathfrak{t}$  be a sector-germ of  $B$  such that there exists a minimal gallery  $\mathfrak{t} = \mathfrak{s}_0, \dots, \mathfrak{s}_{n-1} = \mathfrak{s}$  from  $\mathfrak{t}$  to  $\mathfrak{s}$ . By Lemma 3.6, there exist opposite half-apartments  $D_1, D_2$  of  $B$  such that for both  $i \in \{1, 2\}$ ,  $D_i \cup \mathfrak{s}_1$  is contained in an apartment  $B_i$ . Let  $i \in \{1, 2\}$ . One has  $d_{\mathfrak{s}}(B_i) = n - 1$  and thus  $B_i = \bigcup_{j=1}^{k_i} P_j^{(i)}$ , with  $k_i \leq 2^{n-1}$ , for all  $j \in \llbracket 1, k_i \rrbracket$ ,  $P_j^{(i)} \in \mathcal{P}_{B_i, n-1}$  and  $\mathfrak{s}, P_j^{(i)}$  is contained in some apartment  $A_j^{(i)}$ . One has

$$B = D_1 \cup D_2 = B_1 \cap D_1 \cup B_2 \cap D_2 = \bigcup_{i \in \{1, 2\}, j \in \llbracket 1, k_i \rrbracket} P_j^{(i)} \cap D_i.$$

Let  $i \in \{1, 2\}$ ,  $j \in \llbracket 1, k_i \rrbracket$  and  $\phi_i : B_i \xrightarrow{B \cap B_i} B$ . Then  $P_j^{(i)} \cap D_i = \phi_i(P_j^{(i)} \cap D_i) \in \mathcal{P}_{B,n}$  and  $B_i \supset (P_j^{(i)} \cap D_i), \mathfrak{s}$ .

Let  $f_i^{(j)} : A_i^{(j)} \xrightarrow{P_i^{(j)}} B_i$  and  $f = \phi_i \circ f_i^{(j)}$ . Then  $f : A_j^{(i)} \xrightarrow{P_j^{(i)} \cap D_i} B$  and the proposition follows.  $\square$

We deduce from the previous proposition a corollary which was already known for mesures associated to split Kac-Moody groups over fields equipped with a nonarchimedean discrete valuation by Section 4.4 of [GR08]:

**Corollary 3.8.** *Let  $\mathfrak{s}$  be a sector-germ,  $A$  be an apartment and  $x, y \in A$ . Then there exists  $x = x_1, \dots, x_k = y \in [x, y]_A$  such that  $[x, y]_A = \bigcup_{i=1}^{k-1} [x_i, x_{i+1}]_A$  and such that for all  $i \in \llbracket 1, k-1 \rrbracket$ ,  $\mathfrak{s} \cup [x_i, x_{i+1}]_A$  is contained in an apartment  $A_i$  such that there exists an isomorphism  $f_i : A \xrightarrow{[x_i, x_{i+1}]_{A_i}} A_i$ .*

### 3.3 Restrictions on the distances

In this subsection, we show that some properties cannot be satisfied by distances on mesures. If  $A$  is an apartment of  $\mathcal{I}$ , we show that there exist apartments branching at every wall of  $A$  (this is Lemma 3.9). This implies that if  $\mathcal{I}$  is not a building the interior of each apartment is empty for the distances we study. We write  $\mathcal{I}$  as a countable union of apartments and then use Baire's Theorem to show that under a rather weak assumption of regularity for retractions, a measure cannot be complete nor locally compact for the distances we study.

Let us show a slight refinement of Corollaire 2.10 of [Rou11]:

**Lemma 3.9.** *Let  $A$  be an apartment of  $\mathcal{I}$  and  $D$  be a half-apartment of  $A$ . Then there exists an apartment  $B$  such that  $A \cap B = D$ .*

*Proof.* Let  $M$  be the wall of  $D$ ,  $P$  be a panel of  $M$  and  $C$  be a chamber whose closure contains  $P$  and which is not contained in  $A$ . By Proposition 2.9 1) of [Rou11], there exists an apartment  $B$  containing  $D$  and  $C$ . By Lemma 3.2,  $A \cap B = D$ , which proves the lemma.  $\square$

**Proposition 3.10.** *Assume that there exists a distance  $d_{\mathcal{I}}$  on  $\mathcal{I}$  such that for every apartment  $A$ ,  $d_{\mathcal{I}|A^2}$  is induced by some norm. Then  $\mathcal{I}$  is a building and  $d_{\mathcal{I}|A^2}$  is  $W^a$ -invariant.*

*Proof.* Let  $\mathfrak{s}$  be a sector-germ and  $A, B$  be two apartments containing  $\mathfrak{s}$ . Let  $\phi : A \xrightarrow{A \cap B} B$ . Let us first prove that  $\phi : (A, d_{\mathcal{I}}) \rightarrow (B, d_{\mathcal{I}})$  is an isometry. Let  $d' : A \times A \rightarrow \mathbb{R}_+$  be defined by  $d'(x, y) = d_{\mathcal{I}}(\phi(x), \phi(y))$  for all  $x, y \in A$ . Then  $d'$  is induced by some norm. Moreover  $d'_{|(A \cap B)^2} = d_{\mathcal{I}|(A \cap B)^2}$ . As  $A \cap B$  has nonempty interior, we deduce that  $d' = d_{\mathcal{I}}$  and thus  $\phi : (A, d_{\mathcal{I}}) \rightarrow (B, d_{\mathcal{I}})$  is an isometry.

Let  $M$  be a wall of  $\mathbb{A}$ ,  $D_1$  and  $D_2$  be the half-apartments defined by  $M$  and  $s \in W^a$  be the reflection with respect to  $M$ . Let  $A_2$  be an apartment of  $\mathcal{I}$  such that  $A \cap A_2 = D_1$ , which exists by Lemma 3.9. Let  $D_3$  be the half-apartment of  $B$  opposite to  $D_1$ . Then  $D_3 \cap D_2 \subset D_3 \cap \mathbb{A} \subset M$  and thus  $D_2 \cap D_3 = M$ . By Proposition 2.9 2) of [Rou11],  $D_3 \cup D_2$  is an apartment  $A_1$  of  $\mathcal{I}$ . Let  $\phi_2 : \mathbb{A} \xrightarrow{A \cap A_1} A_1$ ,  $\phi_1 : \mathbb{A} \xrightarrow{A \cap A_2} A_2$  and  $\phi_3 : A_1 \xrightarrow{A_1 \cap A_2} A_2$ . Then by Lemma 3.4, the following diagram is commutative:

$$\begin{array}{ccc} \mathbb{A} & \xrightarrow{s} & \mathbb{A} \\ \downarrow \phi_2 & & \downarrow \phi_1 \\ A_1 & \xrightarrow{\phi_3} & A_2 \end{array}.$$

By the first part of the proof,  $s$  is an isometry of  $\mathbb{A}$  and thus  $W^a$  is a group of isometries for  $d_{\mathcal{I}|A^2}$ . By Proposition 2.1 (1),  $W^v$  is finite and by [Rou11] 2.2 6),  $\mathcal{I}$  is a building.  $\square$

**Lemma 3.11.** *Let  $\mathfrak{s}$  be a sector-germ of  $\mathcal{I}$  and  $d$  be a distance on  $\mathcal{I}$  inducing the affine topology on each apartment and such that there exists a continuous retraction  $\rho$  of  $\mathcal{I}$  centered at  $\mathfrak{s}$ . Then each apartment containing  $\mathfrak{s}$  is closed.*

*Proof.* Let  $A$  be an apartment containing  $\mathfrak{s}$  and  $B = \rho(\mathcal{I})$ . Let  $\phi : B \xrightarrow{\mathfrak{s}} A$  and  $\rho_A : \mathcal{I} \xrightarrow{\mathfrak{s}} A$ . Then  $\rho_A = \phi \circ \rho$  is continuous because  $\phi$  is an affine map. Let  $(x_n) \in A^{\mathbb{N}}$  be a converging sequence for  $d$  and  $x = \lim x_n$ . Then  $x_n = \rho_A(x_n) \rightarrow \rho_A(x)$  and thus  $x = \rho_A(x) \in A$ .  $\square$

**Proposition 3.12.** *Suppose  $\mathcal{I}$  is not a building. Let  $d$  be a distance on  $\mathcal{I}$  inducing the affine topology on each apartment. Then the interior of each apartment of  $\mathcal{I}$  is empty.*

*Proof.* Let  $V$  be a nonempty open set of  $\mathcal{I}$ . Let  $A$  be an apartment of  $\mathcal{I}$  such that  $A \cap V \neq \emptyset$ . By Proposition 2.1 (2), there exists a wall  $M$  of  $A$  such that  $M \cap V \neq \emptyset$ . Let  $D$  be a half-apartment delimited by  $M$ . Let  $B$  be an apartment such that  $A \cap B = D$ , which exists by Lemma 3.9. Then  $B \cap V$  is an open set of  $B$  containing  $M \cap V$  and thus  $E \cap V \neq \emptyset$ , where  $E$  is the half-apartment of  $B$  opposite to  $D$ . Therefore  $V \setminus A \neq \emptyset$  and we get the proposition.  $\square$

One sets  $\mathcal{I}_0 = G.0$  where  $0 \in \mathbb{A}$ . This is the set of *vertices of type 0*. Recall that  $\pm\infty = \text{germ}_\infty(\pm C_f^v)$  and that  $\rho_{\pm\infty} : \mathcal{I} \xrightarrow{\pm\infty} \mathbb{A}$ .

**Lemma 3.13.** *One has  $\mathcal{I}_0 \cap \mathbb{A} = Y$ .*

*Proof.* Let  $\lambda \in \mathcal{I}_0 \cap \mathbb{A}$ . Then  $\lambda = g.0$  for some  $g \in G$ . By (MA2), there exists  $\phi : g.\mathbb{A} \rightarrow \mathbb{A}$  fixing  $\lambda$ . Then  $\lambda = \phi(g.0)$  and  $\phi \circ g|_{\mathbb{A}} : \mathbb{A} \rightarrow \mathbb{A}$  is an automorphism of apartments. Let  $h \in G$  inducing  $\phi$  on  $g.\mathbb{A}$ . Then  $h.g \in N$ , hence  $(h.g)|_{\mathbb{A}} \in \nu(N) = W^v \ltimes Y$  (by the end of Subsection 2.6) and thus  $\lambda = h.g.0 \in Y$ .  $\square$

**Lemma 3.14.** *The set  $\mathcal{I}_0$  is countable.*

*Proof.* For all  $\lambda \in \mathcal{I}_0$ ,  $\rho_{-\infty}(\lambda), \rho_{+\infty}(\lambda) \in \mathcal{I}_0$  and thus  $\rho_{-\infty}(\lambda), \rho_{+\infty}(\lambda) \in Y$ . Therefore  $\mathcal{I}_0 = \bigcup_{(\lambda, \mu) \in Y^2} \rho_{-\infty}^{-1}(\{\lambda\}) \cap \rho_{+\infty}^{-1}(\{\mu\})$ . By Theorem 5.6 of [Héb17],  $\rho_{-\infty}^{-1}(\{\lambda\}) \cap \rho_{+\infty}^{-1}(\{\mu\})$  is finite for all  $(\lambda, \mu) \in Y^2$ , which completes the proof.  $\square$

Let  $\mathfrak{s}$  be a sector-germ of  $\mathcal{I}$ . For  $\lambda \in \mathcal{I}_0$  choose an apartment  $A(\lambda)$  containing  $\lambda + \mathfrak{s}$ . Let  $x \in \mathcal{I}$  and  $A$  be an apartment containing  $x$  and  $\mathfrak{s}$ . Then there exists  $\lambda \in \mathcal{I}_0 \cap A$  such that  $x \in \lambda + \mathfrak{s}$  and thus  $x \in A(\lambda)$ . Therefore  $\mathcal{I} = \bigcup_{\lambda \in \mathcal{I}_0} A(\lambda)$ .

**Proposition 3.15.** *Let  $d$  be a distance on  $\mathcal{I}$ . Suppose that there exists a sector-germ  $\mathfrak{s}$  such that every apartment containing  $\mathfrak{s}$  is closed and with empty interior. Then  $(\mathcal{I}, d)$  is not complete and the interior of every compact subset of  $\mathcal{I}$  is empty.*

*Proof.* One has  $\mathcal{I} = \bigcup_{\lambda \in \mathcal{I}_0} A(\lambda)$ , with  $\mathcal{I}_0$  countable by Lemma 3.14. Thus by Baire's Theorem,  $(\mathcal{I}, d)$  is not complete.

Let  $K$  be a compact subset of  $\mathcal{I}$ . Then  $K = \bigcup_{\lambda \in \mathcal{I}_0} K \cap A(\lambda)$  and thus  $K$  has empty interior.  $\square$

## 4 Distances of positive type and of negative type

### 4.1 Translation in a direction

Let  $\mathfrak{s}$  be a sector-germ. We now define a map  $+_{\mathfrak{s}}$  such that for all  $x \in \mathcal{I}$  and  $u \in \overline{C_f^v}$ ,  $x +_{\mathfrak{s}} u$  is the “translate of  $x$  by  $u$  in the direction  $\mathfrak{s}$ ”. Let  $\text{sgn}(\mathfrak{s}) \in \{-, +\}$  be the sign of  $\mathfrak{s}$ .



**Definition/Proposition 4.1.** Let  $\mathfrak{s}$  be a sector-germ. Let  $x \in \mathcal{I}$ . Let  $A_1$  be an apartment containing  $x + \mathfrak{s}$ . Let  $(x + \bar{\mathfrak{s}})_{A_1}$  be the closure of  $x + \mathfrak{s}$  in  $A_1$ . Then  $(x + \bar{\mathfrak{s}})_{A_1}$  does not depend on the choice of  $A_1$  and we denote it by  $x + \bar{\mathfrak{s}}$ .

*Proof.* Let  $A_2$  be an apartment containing  $x + \mathfrak{s}$  and  $\phi : A_1 \xrightarrow{A_1 \cap A_2} A_2$ . By (MA4),  $\phi$  fixes the enclosure of  $x + \mathfrak{s}$ , which contains  $(x + \bar{\mathfrak{s}})_{A_1}$ . Therefore  $(x + \bar{\mathfrak{s}})_{A_1} \supset (x + \bar{\mathfrak{s}})_{A_2}$  and by symmetry,  $(x + \bar{\mathfrak{s}})_{A_1} = (x + \bar{\mathfrak{s}})_{A_2}$ . Proposition follows.  $\square$

If  $A$  and  $B$  are apartments and  $\psi : A \rightarrow B$  is an isomorphism, then  $\psi$  induces a bijection still denoted  $\psi$  between the sector-germs of  $A$  and those of  $B$ .

**Definition/Proposition 4.2.** Let  $\mathfrak{s}$  be a sector-germ. Let  $x \in \mathcal{I}$  and  $A_1$  be an apartment containing  $x + \mathfrak{s}$ . Let  $u \in \overline{C_f^v}$  and  $\psi_1 : \mathbb{A} \rightarrow A_1$  be an isomorphism such that  $\psi_1(\text{sgn}(\mathfrak{s})\infty) = \mathfrak{s}$ . Then  $\psi_1(\psi_1^{-1}(x + \text{sgn}(\mathfrak{s})u))$  does not depend on the choice of  $A_1$  and of  $\psi_1$  and we denote it  $x +_{\mathfrak{s}} u$ . Moreover  $x +_{\mathfrak{s}} C_f^v = x + \mathfrak{s}$  and  $x +_{\mathfrak{s}} \overline{C_f^v} = x + \bar{\mathfrak{s}}$ .

*Proof.* As the case where  $\mathfrak{s}$  is negative is similar, we assume that  $\mathfrak{s}$  is positive.

We first prove the independence of the choice of isomorphism. Let  $\psi'_1 : \mathbb{A} \rightarrow A_1$  be an isomorphism such that  $\psi'_1(+\infty) = \mathfrak{s}$ . Then  $\psi'^{-1}_1 \circ \psi_1 \in W^v \ltimes Y$  fixes the direction  $+\infty$  and thus  $\psi'^{-1}_1 \circ \psi_1$  is a translation of  $\mathbb{A}$ . Therefore

$$\psi'^{-1}_1 \circ \psi_1(\psi_1^{-1}(x) + u) = \psi'^{-1}_1 \circ \psi_1(\psi_1^{-1}(x)) + u = \psi'^{-1}_1(x) + u,$$

and thus

$$\psi_1(\psi_1^{-1}(x + u)) = \psi'_1(\psi'^{-1}_1(x + u)).$$

Let now  $A_2$  be an apartment containing  $x + \mathfrak{s}$  and  $\psi_2 : \mathbb{A} \rightarrow A_2$  be an isomorphism such that  $\psi_2(+\infty) = \mathfrak{s}$ . From what has already been proved, we can assume that  $\psi_2 \circ \psi_1^{-1} = \phi$ , where  $\phi : A_1 \xrightarrow{A_1 \cap A_2} A_2$ .

As  $x \in A_1 \cap A_2$ ,  $\phi(x) = x$  and thus

$$\psi_1^{-1}(x) = \psi_2^{-1}(x).$$

Let  $i \in \{1, 2\}$ . Then  $\psi_i(\psi_i^{-1}(x) + C_f^v)$  is a sector with the base point  $x$  and with the direction  $\mathfrak{s}$ :  $\psi_i(\psi_i^{-1}(x) + C_f^v) = x + \mathfrak{s}$  (see Proposition 2.3). Moreover  $\psi_i(\psi_i^{-1}(x) + \overline{C_f^v})$  is the closure of  $\psi_i(\psi_i^{-1}(x) + C_f^v) = x + \mathfrak{s}$  in  $A_i$  and thus  $\psi_i(\psi_i^{-1}(x) + \overline{C_f^v}) = x + \bar{\mathfrak{s}}$ .

Consequently  $\psi_1(\psi_1^{-1}(x + u)) \in x + \bar{\mathfrak{s}} \subset A_1 \cap A_2$ . Thus

$$\phi\left(\psi_1(\psi_1^{-1}(x + u))\right) = \psi_1(\psi_1^{-1}(x + u)) = \psi_2(\psi_1^{-1}(x) + u) = \psi_2(\psi_2^{-1}(x) + u),$$

which is our assertion.  $\square$

Through the end of this section, we fix a sector-germ  $\mathfrak{s}$ . As the case where  $\mathfrak{s}$  is negative is similar to the case where it is positive, we assume that  $\mathfrak{s}$  is positive.

**Lemma 4.3.** Let  $x \in \mathcal{I}$  and  $u, u' \in \overline{C_f^v}$ . Then  $(x +_{\mathfrak{s}} u) +_{\mathfrak{s}} u' = x +_{\mathfrak{s}} (u + u')$ .

*Proof.* Let  $A$  be an apartment containing  $x + \mathfrak{s}$  and  $\psi : \mathbb{A} \rightarrow A$  be such that  $\psi(+\infty) = \mathfrak{s}$ . One has  $(x +_{\mathfrak{s}} u) +_{\mathfrak{s}} u', x +_{\mathfrak{s}} (u + u') \in A$ . By definition,  $\psi^{-1}(x +_{\mathfrak{s}} u) = \psi^{-1}(x) + u$ , thus

$$(x +_{\mathfrak{s}} u) +_{\mathfrak{s}} u' = \psi(\psi^{-1}(x +_{\mathfrak{s}} u) + u') = \psi(\psi^{-1}(x) + u + u') = x +_{\mathfrak{s}} (u + u'),$$

which proves the lemma.  $\square$



For  $x, x' \in \mathcal{I}$ , we set  $U_{\mathfrak{s}}(x, x') = \{(u, u') \in \overline{C_f^v}^2 \mid x +_{\mathfrak{s}} u = x' +_{\mathfrak{s}} u'\}$ .

**Lemma 4.4.** *Let  $x, x' \in \mathcal{I}$ . Then  $U_{\mathfrak{s}}(x, x')$  is nonempty.*

*Proof.* Let  $A$  be an apartment containing  $\mathfrak{s}$ . Choose  $a \in (x + \mathfrak{s}) \cap A$  and  $a' \in (x' + \mathfrak{s}) \cap A$ . Then  $a + \mathfrak{s}$  and  $a' + \mathfrak{s}$  are sectors of  $A$  of the same direction and thus there exists  $b \in (a + \mathfrak{s}) \cap (a' + \mathfrak{s})$ . By Definition/Proposition 4.2, there exist  $u, u', v, v' \in C_f^v$  such that  $a = x +_{\mathfrak{s}} u$ ,  $a' = x' +_{\mathfrak{s}} u'$  and  $b = a +_{\mathfrak{s}} v = a' +_{\mathfrak{s}} v'$ . By Lemma 4.3,  $(u + v, u' + v') \in U_{\mathfrak{s}}(x, x')$  and the lemma is proved.  $\square$

## 4.2 Definition of distances of positive type and of negative type

Let  $\Theta_+$  (resp.  $\Theta_-$ ) be the set of pairs  $(|\cdot|, \mathfrak{s})$  such that  $\mathfrak{s}$  is a positive (resp. negative) sector-germ and  $|\cdot|$  is a norm on  $\mathbb{A}$ .

**Definition/Proposition 4.5.** *Let  $\theta = (|\cdot|, \mathfrak{s}) \in \Theta_+ \cup \Theta_-$ . Let  $d_{\theta} : \mathcal{I}^2 \rightarrow \mathbb{R}_+$  be defined by  $d_{\theta}(x, x') = \inf\{|u| + |u'| \mid (u, u') \in U_{\mathfrak{s}}(x, x')\}$  for all  $x, x' \in \mathcal{I}$ . Then  $d_{\theta}$  is a distance on  $\mathcal{I}$ .*

*Proof.* By Lemma 4.4,  $d_{\theta}$  is well defined. Moreover it is clearly symmetric.

Let us show the triangle inequality. Let  $x, x', x'' \in \mathcal{I}$ . Let  $\epsilon > 0$  and let  $(u, u') \in U_{\mathfrak{s}}(x, x')$ ,  $(v', v'') \in U_{\mathfrak{s}}(x', x'')$  be such that  $|u| + |u'| \leq d_{\theta}(x, x') + \epsilon$  and  $|v'| + |v''| \leq d_{\theta}(x', x'') + \epsilon$ . One has  $x +_{\mathfrak{s}} u = x' +_{\mathfrak{s}} u'$  and  $x' +_{\mathfrak{s}} v' = x'' +_{\mathfrak{s}} v''$ . Thus  $x +_{\mathfrak{s}} u +_{\mathfrak{s}} v' = x' +_{\mathfrak{s}} u' +_{\mathfrak{s}} v' = x'' +_{\mathfrak{s}} v'' +_{\mathfrak{s}} u'$  (by Lemma 4.3) and hence  $(u + v', v'' + u') \in U_{\mathfrak{s}}(x, x'')$ . Consequently,  $d_{\theta}(x, x'') \leq |u + v'| + |v'' + u'| \leq |u| + |v'| + |v''| + |u'| \leq d_{\theta}(x, x') + d_{\theta}(x', x'') + 2\epsilon$ , which proves the triangle inequality.

Let  $x, x' \in \mathcal{I}$  be such that  $d_{\theta}(x, x') = 0$ . Then there exist  $((u_n, u'_n))_{n \in \mathbb{N}} \in U_{\mathfrak{s}}(x, x')^{\mathbb{N}}$  such that  $u_n \rightarrow 0$  and  $u'_n \rightarrow 0$ . Let  $n \in \mathbb{N}$ . One has  $x + \mathfrak{s} \supset x +_{\mathfrak{s}} u_n + \mathfrak{s} = x' +_{\mathfrak{s}} u'_n + \mathfrak{s}$  and thus  $x + \mathfrak{s} \supset \bigcup_{n \in \mathbb{N}} x' + u'_n + \mathfrak{s} = x' + \mathfrak{s}$ . By symmetry,  $x' + \mathfrak{s} \supset x + \mathfrak{s}$  and hence  $x + \mathfrak{s} = x' + \mathfrak{s}$ . Let  $B$  be an apartment containing  $x$  and  $\mathfrak{s}$ . By (MA2),  $B \supset \text{cl}(x + \mathfrak{s}) = \text{cl}(x' + \mathfrak{s}) \ni x'$ . Therefore  $x = x'$ .  $\square$

Thus we have constructed a distance  $d_{\theta}$  for all  $\theta \in \Theta_+ \cup \Theta_-$ . A distance of the form  $d_{\theta_+}$  (resp.  $d_{\theta_-}$ ) for some  $\theta_+ \in \Theta_+$  (resp.  $\theta_- \in \Theta_-$ ) is called a *distance of positive type* (resp. *distance of negative type*). When  $\mathcal{I}$  is a tree, we obtain the usual distance.

## 4.3 Study on the apartments containing $\mathfrak{s}$

We now study the  $d_{\theta}$ , for  $\theta \in \Theta_+ \cup \Theta_-$ . In order to simplify the notation and by symmetry, we will mainly take  $\theta \in \Theta_+$ .

Fix  $\theta \in \Theta_+$ . Write  $\theta = (|\cdot|, \mathfrak{s})$ , where  $|\cdot|$  is a norm and  $\mathfrak{s}$  is a sector-germ. We have similar results for  $\theta \in \Theta_-$ .

**Lemma 4.6.** *Let  $A$  and  $B$  be two apartments containing  $\mathfrak{s}$ . Set  $\rho : \mathcal{I} \xrightarrow{\mathfrak{s}} A$  and  $\phi : A \xrightarrow{A \cap B} B$ . Then:*

1. *the distance  $d_{\theta|_{A^2}}$  is induced by some norm on  $A$ ,*
2. *for all  $x \in \mathcal{I}$  and  $u \in \overline{C_f^v}$ ,  $\rho(x +_{\mathfrak{s}} u) = \rho(x) +_{\mathfrak{s}} u$ ,*
3. *the retraction  $\rho : (\mathcal{I}, d_{\theta}) \rightarrow (A, d_{\theta|_{A^2}})$  is 1-Lipschitz continuous,*
4. *the map  $\phi : (A, d_{\theta|_{A^2}}) \rightarrow (B, d_{\theta|_{B^2}})$  is an isometry.*

*Proof.* Let us prove 1. Let  $\psi : \mathbb{A} \rightarrow A$  be such that  $\psi(+\infty) = \mathfrak{s}$ . Let  $|\cdot|' : \mathbb{A} \rightarrow \mathbb{R}^+$  be defined by  $|a|' = d_\theta(\psi(a), \psi(0))$  for all  $a \in \mathbb{A}$ .

For  $a_1, a_2 \in \mathbb{A}$ , set  $V(a_1, a_2) = \{(u_1, u_2) \in \overline{C_f^v} \mid a_1 - a_2 = u_2 - u_1\}$ . Let  $(a_1, a_2) \in A$ . Let  $i \in \{1, 2\}$  and  $u_i \in \overline{C_f^v}$ . Then  $a_i +_{\mathfrak{s}} u_i = \psi(\psi^{-1}(a_i) + u_i)$  and thus

$$U_{\mathfrak{s}}(a_1, a_2) = V(\psi^{-1}(a_1), \psi^{-1}(a_2)).$$

Let  $a_1, a_2$ . Then  $U_{\mathfrak{s}}(a_1, a_2) = V(\psi^{-1}(a_1), \psi^{-1}(a_2)) = V(\psi^{-1}(a_1) - \psi^{-1}(a_2), 0)$ . Consequently  $d_\theta(a_1, a_2) = |\psi^{-1}(a_1) - \psi^{-1}(a_2)|'$ . It remains to prove that  $|\cdot|'$  is a norm on  $\mathbb{A}$ . Let  $a_1, a_2 \in \mathbb{A}$ . Then

$$|a_1 + a_2|' = d_\theta(\psi(a_1 + a_2), \psi(0)) \leq d_\theta(\psi(a_1 + a_2), \psi(a_1)) + d_\theta(\psi(a_1), \psi(0))$$

by Definition/Proposition 4.5. As  $V(a_1 + a_2, a_1) = V(a_2, 0)$ , we deduce that  $d_\theta(\psi(a_1 + a_2), \psi(a_1)) = d_\theta(\psi(a_2), \psi(0))$  and hence  $|a_1 + a_2|' \leq |a_1|' + |a_2|'$ .

Let  $t \in \mathbb{R}$  and  $a \in \mathbb{A}$ . As  $V(0, ta) = tV(0, a)$ , we deduce that  $|ta|' = |t||a|'$ , which proves 1.

Let us prove 2. Let  $x \in \mathcal{I}$  and  $A_x$  be an apartment containing  $x + \mathfrak{s}$ . Let  $\phi : A_x \xrightarrow{A_x \cap A} A$ . Let  $\psi_x : \mathbb{A} \rightarrow A_x$  be such that  $\psi_x(+\infty) = \mathfrak{s}$  and  $\psi_A = \phi \circ \psi_x$ . Then  $\psi_A(+\infty) = \mathfrak{s}$ . Let  $u \in \overline{C_f^v}$ . Then by Definition/Proposition 4.2,  $A_x \ni x +_{\mathfrak{s}} u$  and  $A \ni \rho(x) +_{\mathfrak{s}} u$ . Therefore

$$\rho(x +_{\mathfrak{s}} u) = \phi(x +_{\mathfrak{s}} u) = \phi \circ \psi_x(\psi_x^{-1}(x) + u) = \psi_A(\psi_x^{-1}(x) + u)$$

and

$$\rho(x) +_{\mathfrak{s}} u = \psi_A(\psi_A^{-1}(\rho(x)) + u) = \psi_A(\psi_x^{-1}(x) + u) = \rho(x +_{\mathfrak{s}} u),$$

which proves 2.

By 2, for all  $x, x' \in \mathcal{I}$ ,  $U_{\mathfrak{s}}(\rho(x), \rho(x')) \supset U_{\mathfrak{s}}(x, x')$ , which proves 3. By 3,  $\phi^{-1} : (B, d_{\theta|B^2}) \rightarrow (A, d_{\theta|A^2})$  is 1-Lipschitz continuous. By symmetry,  $\phi : (A, d_{\theta|A^2}) \rightarrow (B, d_{\theta|B^2})$  is 1-Lipschitz continuous, which proves 4. □

**Lemma 4.7.** *Let  $d'$  be a distance on  $\mathbb{A}$  induced by some norm on  $\mathbb{A}$ . Define  $d_{\theta, d'} : \mathcal{I} \times \overline{C_f^v} \rightarrow \mathbb{R}_+$  by  $d_{\theta, d'}((x, u), (x', u')) = d_\theta(x, x') + d'(u, u')$  for all  $(x, u), (x', u') \in \mathcal{I} \times \overline{C_f^v}$ . Then the map  $(\mathcal{I} \times \overline{C_f^v}, d_{\theta, d'}) \rightarrow (\mathcal{I}, d_\theta)$  defined by  $(x, u) \mapsto x +_{\mathfrak{s}} u$  is Lipschitz continuous.*

*Proof.* Using isomorphisms of apartments, we may assume that  $\mathfrak{s}$  is contained in  $\mathbb{A}$ . By the fact that all the norms on  $\mathbb{A}$  are equivalent, it suffices to prove the assertion for a particular choice of  $d'$ . We choose  $d' = d_{\theta|_{\mathbb{A}^2}}$ , which is possible by Lemma 4.6 (1). We regard  $\overline{C_f^v}$  as a subset of  $\mathcal{I}$ .

Let  $(x, u), (x', u') \in \mathcal{I} \times \overline{C_f^v}$ . Let  $\epsilon > 0$ . Let  $(u, u') \in U_{\mathfrak{s}}(x, x')$  and  $(v, v') \in U_{\mathfrak{s}}(u, u')$  be such that  $|u| + |u'| \leq d_\theta(x, x') + \epsilon$  and  $|v| + |v'| \leq d_\theta(u, u') + \epsilon$ . By Lemma 4.3,  $(u + v, u' + v') \in U_{\mathfrak{s}}(x +_{\mathfrak{s}} u, x' +_{\mathfrak{s}} u')$ , thus  $d_\theta(x + u, x' + u') \leq |u| + |v| + |u'| + |v'| \leq d_\theta(x, x') + d_\theta(u, u') + 2\epsilon$  and hence  $d_\theta(x + u, x' + u') \leq d_\theta(x, x') + d_\theta(u, u') = d_{\theta, d'}((x, u), (x', u'))$ . Lemma follows. □

**Lemma 4.8.** *For all  $x, x' \in \mathcal{I}$ , there exists  $(u, u') \in U_{\mathfrak{s}}(x, x')$  such that  $d_\theta(x, x') = |u| + |u'|$ .*

*Proof.* Let  $x, x' \in \mathcal{I}$  and let  $((u_n, u'_n)) \in U_{\mathfrak{s}}(x, x')^{\mathbb{N}}$  be such that  $|u_n| + |u'_n| \rightarrow d_\theta(x, x')$ . Then  $(|u_n|), (|u'_n|)$  are bounded and thus extracting subsequences if necessary, one can assume that  $(u_n)$  and  $(u'_n)$  converge in  $(\overline{C_f^v}, |\cdot|)$ . Lemma 4.7 implies that  $(\lim u_n, \lim u'_n) \in U_{\mathfrak{s}}(x, x')$ , which proves our assertion. □

## 4.4 Geodesics in $\mathcal{I}$

Fix  $\theta = (|\cdot|, \mathfrak{s}) \in \Theta_+$ . We now prove that for all  $x_1, x_2 \in \mathcal{I}$ , there exists a geodesic for  $d_\theta$  between  $x_1$  and  $x_2$ . However we prove that such a geodesic is in general not unique. Using isomorphisms of apartments, we may assume that  $\mathfrak{s} = +\infty$ . For all  $x \in \mathbb{A}$  and  $u \in \overline{C_f^v}$ ,  $x +_{+\infty} u = x + u$ . To simplify the notation we write  $+$  instead of  $+\infty$ .

**Lemma 4.9.** *1. Let  $x_1, x_2 \in \mathcal{I}$  and let  $(u_1, u_2) \in U_{+\infty}(x_1, x_2)$  be such that  $d_\theta(x_1, x_2) = |u_1| + |u_2|$ . Then for both  $i \in \{1, 2\}$  and all  $t, t' \in [0, 1]$ ,*

$$d_\theta(x_i + tu_i, x_i + t'u_i) = |t' - t||u_i|$$

and

$$d_\theta(x_1 + tu_1, x_2 + t'u_2) = (1 - t)|u_1| + (1 - t')|u_2|.$$

*2. Let  $x \in \mathbb{A}$  and  $(u_1, u_2) \in U_{+\infty}(0, x)$  be such that  $d_\theta(0, x) = |u_1| + |u_2|$ . Then for all  $t_1, t'_1, t_2, t'_2 \in [0, 1]$  such that  $t_1 \leq t'_1$  and  $t_2 \leq t'_2$ ,*

$$d_\theta(t_1 u_1 - t_2 u_2, t'_1 u_1 - t'_2 u_2) = (t'_1 - t_1)|u_1| + (t'_2 - t_2)|u_2|.$$

*Proof.* Let  $t, t' \in [0, 1]$ . We assume  $t \leq t'$ . Let  $i \in \{1, 2\}$  and let  $j$  be such that  $\{i, j\} = \{1, 2\}$ . As  $x_i + u_i = x_j + u_j$ ,

$$\begin{aligned} d_\theta(x_1, x_2) &\leq d_\theta(x_i, x_i + tu_i) + d_\theta(x_i + tu_i, x_i + t'u_i) \\ &\quad + d_\theta(x_i + t'u_i, x_i + u_i) + d_\theta(x_j + u_j, x_j). \end{aligned}$$

By definition of  $d_\theta$ ,  $d_\theta(x_i, x_i + tu_i) \leq t|u_i|$ ,  $d_\theta(x_i + tu_i, x_i + t'u_i) \leq (t' - t)|u_i|$ ,  $d_\theta(x_i + t'u_i, x_i + u_i) \leq (1 - t')|u_i|$  and  $d_\theta(x_j + u_j, x_j) \leq |u_j|$ . As

$$d_\theta(x_1, x_2) = |u_1| + |u_2| = t|u_i| + (t' - t)|u_i| + (1 - t')|u_i| + |u_j|$$

we deduce that  $d_\theta(x_i, x_i + tu_i) = t|u_i|$ ,  $d_\theta(x_i + tu_i, x_i + t'u_i) = (t' - t)|u_i|$ ,  $d_\theta(x_i + t'u_i, x_i + u_i) = (1 - t')|u_i|$  and  $d_\theta(x_j + u_j, x_j) = |u_j|$ .

We no more assume  $t \leq t'$ . One has

$$\begin{aligned} d_\theta(x_1 + tu_1, x_2 + t'u_2) &\geq d_\theta(x_1, x_2) - d_\theta(x_1, x_1 + tu_1) - d_\theta(x_2, x_2 + t'u_2) \\ &= (1 - t)|u_1| + (1 - t')|u_2|. \end{aligned}$$

Moreover

$$\begin{aligned} d_\theta(x_1 + tu_1, x_2 + t'u_2) &\leq d_\theta(x_1 + tu_1, x_1 + u_1) + d_\theta(x_2 + u_2, x_2 + t'u_2) \\ &= (1 - t)|u_1| + (1 - t')|u_2|, \end{aligned}$$

which proves 1. A similar argument proves 2. □

**Proposition 4.10.** *Equip  $\mathcal{I}$  with  $d_\theta$ . For all  $x_1, x_2 \in \mathcal{I}$ , there exists a geodesic from  $x_1$  to  $x_2$ . Moreover, if  $\dim \mathbb{A} \geq 2$ , there exists a pair  $(x_1, x_2) \in \mathcal{I}^2$  such that there exists infinitely many geodesics from  $x_1$  to  $x_2$ .*

*Proof.* Let  $x_1, x_2 \in \mathcal{I}$ . Let  $(u_1, u_2) \in U_{+\infty}(x_1, x_2)$  be such that  $|u_1| + |u_2| = d_\theta(x_1, x_2)$ . Let  $a_1 = \frac{|u_1|}{|u_1| + |u_2|}$  and  $a_2 = 1 - a_1$ . Set  $\frac{1}{0}u_1 = \frac{1}{0}u_2 = 0$ .

Let  $\gamma : [0, 1] \rightarrow \mathcal{I}$  be defined by  $\gamma(t) = x_1 + \frac{t}{a_1}u_1$  if  $t \in [0, a_1]$  and  $\gamma(a_1 + t) = x_2 + (1 - \frac{t}{a_2})u_2$  if  $t \in [a_1, 1]$ . Then by Lemma 4.9 (1), for all  $t, t' \in [0, 1]$ ,  $d_\theta(\gamma(t), \gamma(t')) = |t' - t|(|u_1| + |u_2|)$  and hence  $\gamma$  is a geodesic from  $x_1$  to  $x_2$ .

Let now  $x \in \mathbb{A} \setminus (\overline{C_f^v} \cup \overline{-C_f^v})$ . Let  $(u_1, u_2) \in U_{+\infty}(0, x)$  be such that  $d_\theta(0, x) = |u_1| + |u_2|$ . One has  $x = u_1 - u_2$  and thus  $u_1, u_2 \neq 0$ . Let  $a_1 = \frac{|u_1|}{|u_1| + |u_2|}$  and  $a_2 = 1 - a_1$ .

For  $z \in [0, 1]$  define  $\gamma_z : [0, 1] \rightarrow A$  as follows.

For  $t \in [0, za_1]$ ,  $\gamma_z(t) = t\frac{u_1}{a_1}$ , for  $t \in [za_1, za_1 + a_2]$ ,  $\gamma_z(t) = zu_1 - (t - za_1)\frac{u_2}{a_2}$  and for  $t \in [za_1 + a_2, 1]$ ,  $\gamma_z(t) = (t - a_1)\frac{u_1}{a_1} - u_2$ . Then by Lemma 4.9 (2), for all  $t, t' \in [0, 1]$ ,  $d_\theta(\gamma_z(t), \gamma_z(t')) = |t' - t|(|u_1| + |u_2|)$  and thus  $\gamma_z$  is a geodesic from 0 to  $x$ . As  $x \notin \overline{C_f^v} \cup \overline{-C_f^v}$ ,  $\mathbb{R}u_1 \neq \mathbb{R}u_2$ , thus  $\gamma_z \neq \gamma_{z'}$  for all  $z \neq z'$  and the proposition is proved.  $\square$

## 4.5 Equivalence of the distances of positive type

The aim of this section is to show that if  $\theta_1, \theta_2 \in \Theta_+$ , then  $d_{\theta_1}$  and  $d_{\theta_2}$  are equivalent. Fix a norm  $|\cdot|$  on  $\mathbb{A}$ .

Fix two adjacent positive sector-germs  $\mathfrak{s}$  and  $\mathfrak{s}'$  and set  $\theta = (|\cdot|, \mathfrak{s})$  and  $\theta' = (|\cdot|, \mathfrak{s}')$ . We begin by proving the existence of  $\ell \in \mathbb{R}_+$  such that  $d_{\theta'} \leq \ell d_\theta$  (see Lemma 4.15).

Fix an apartment  $A_0$  containing  $\mathfrak{s}$  and  $\mathfrak{s}'$ , which exists by (MA3). Let  $\rho_{\mathfrak{s}} : \mathcal{I} \xrightarrow{\mathfrak{s}} A_0$  and  $\rho_{\mathfrak{s}'} : \mathcal{I} \xrightarrow{\mathfrak{s}'} A_0$ .

**Lemma 4.11.** *There exists  $\ell_0 \in \mathbb{R}_{>0}$  such that for every apartment  $B$  containing  $\mathfrak{s}$  and  $\mathfrak{s}'$ , for all  $x, x' \in B$ ,  $d_{\theta'}(x, x') \leq \ell_0 d_\theta(x, x')$ .*

*Proof.* By Lemma 4.6 (1) and the fact that all the norms on  $\mathbb{A}$  are equivalent, there exists  $\ell_0 \in \mathbb{R}_{>0}$  such that for all  $x, x' \in A$ ,  $d_{\theta'}(x, x') \leq \ell_0 d_\theta(x, x')$ . Let  $B$  be an apartment containing  $\mathfrak{s}$  and  $\mathfrak{s}'$ . Let  $x, x' \in B$ . By Lemma 4.6 (4),  $d_\theta(x, x') = d_\theta(\rho_{\mathfrak{s}}(x), \rho_{\mathfrak{s}}(x'))$  and  $d_{\theta'}(\rho_{\mathfrak{s}'}(x), \rho_{\mathfrak{s}'}(x')) = d_{\theta'}(x, x')$ . Moreover  $\rho_{\mathfrak{s}'}|_B = \rho_{\mathfrak{s}}|_B$ , which proves the lemma.  $\square$

We now fix an apartment  $B_0$  containing  $\mathfrak{s}$  but not  $\mathfrak{s}'$ . Let  $\mathfrak{F}_\infty$  be the sector-panel direction dominated by  $\mathfrak{s}$  and  $\mathfrak{s}'$ . Using Lemma 3.6, one writes  $B_0 = D_1 \cup D_2$ , where  $D_1$  and  $D_2$  are two opposite half-apartments whose wall contains  $\mathfrak{F}_\infty$  and such that  $D_i \cup \mathfrak{s}$  is contained in some apartment  $B_i$  for both  $i \in \{1, 2\}$ . We assume that  $D_1 \supset \mathfrak{s}$ .

Let  $M_0$  be a wall of  $A_0$  containing  $\mathfrak{F}_\infty$  and  $t_0 : A_0 \rightarrow A_0$  be the reflection with respect to  $M_0$ .

**Lemma 4.12.** *One has:  $\begin{cases} \rho_{\mathfrak{s}}(x) = \rho_{\mathfrak{s}'}(x) & \text{if } x \in D_1 \\ \rho_{\mathfrak{s}}(x) = \tilde{t} \circ \rho_{\mathfrak{s}'}(x) & \text{if } x \in D_2 \end{cases}$ , where  $\tilde{t} = \tau \circ t_0$ , for some translation  $\tau$  of  $A_0$ .*

*Proof.* Let  $\rho_{\mathfrak{s}, B_1} : \mathcal{I} \xrightarrow{\mathfrak{s}} B_1$  and  $\rho_{\mathfrak{s}', B_1} : \mathcal{I} \xrightarrow{\mathfrak{s}'} B_1$ .

Let  $\phi_i : B_0 \xrightarrow{B_0 \cap B_i} B_i$ , for  $i \in \{1, 2\}$  and  $\phi : B_2 \xrightarrow{B_1 \cap B_2} B_1$ . Let  $t$  be the reflection of  $B_1$  with respect to  $D_1 \cap D_2$ . By Lemma 3.4, the following diagram is commutative:

$$\begin{array}{ccc} B_0 & \xrightarrow{\phi_2} & B_2 \\ \downarrow \phi_1 & & \downarrow \phi \\ B_1 & \xrightarrow{t} & B_1. \end{array}$$

Let  $x \in D_1$ . Then  $\rho_{\mathfrak{s}, B_1}(x) = x = \rho_{\mathfrak{s}', B_1}(x)$ . Let  $\phi_3 : B_1 \xrightarrow{B_1 \cap A_0} A_0$ . Then  $\rho_{\mathfrak{s}}(x) = \phi_3(\rho_{\mathfrak{s}, B_1}(x)) = \phi_3(\rho_{\mathfrak{s}', B_1}(x)) = \rho_{\mathfrak{s}'}(x)$ .

Let  $x \in D_2$ . One has  $\rho_{\mathfrak{s}, B_1}(x) = \phi_1(x)$  and  $\rho_{\mathfrak{s}', B_1}(x) = \phi(x)$  and thus  $\rho_{\mathfrak{s}, B_1}(x) = t \circ \rho_{\mathfrak{s}', B_1}(x)$ . Let  $\tilde{t}$  be such that the following diagram commutes:

$$\begin{array}{ccc} B_1 & \xrightarrow{t} & B_1 \\ \downarrow \phi_3 & & \downarrow \phi_3 \\ A_0 & \xrightarrow{\tilde{t}} & A_0. \end{array}$$

Then  $\rho_{\mathfrak{s}}(x) = \tilde{t} \circ \rho_{\mathfrak{s}'}(x)$ .

Moreover  $\tilde{t}$  fixes  $\phi_3(D_1 \cap D_2)$ , which contains  $\mathfrak{F}_\infty$ . Thus  $\tilde{t} = \tau \circ t_0$  for some translation  $\tau$  of  $A_0$  (by Lemma 3.3). □

By Lemma 4.6 (1) and the fact that every affine map on  $A_0$  is Lipschitz continuous, there exists  $\ell_1 \in \mathbb{R}_+$  such that  $t_0 : (A_0, d_{\theta'}) \rightarrow (A_0, d_{\theta'})$  is  $\ell_1$ -Lipschitz continuous. As  $t_0$  is an involution,  $\ell_1 \geq 1$ .

**Lemma 4.13.** *Let  $\ell_0$  be as in Lemma 4.11. Then for all  $x, x' \in B_0$ ,  $d_{\theta'}(x, x') \leq \ell_0 \ell_1 d_{\theta}(x, x')$ .*

*Proof.* Let  $i \in \{1, 2\}$  and  $x, x' \in D_i$ . By Lemma 4.6 (4),  $d_{\theta}(x, y) = d_{\theta}(\rho_{\mathfrak{s}}(x), \rho_{\mathfrak{s}}(x'))$  and  $d_{\theta'}(x, x') = d_{\theta'}(\rho_{\mathfrak{s}'}(x), \rho_{\mathfrak{s}'}(x'))$ . By Lemma 4.12, for all  $x, x' \in D_i$ ,  $d_{\theta'}(x, x') \leq \ell_0 \ell_1 d_{\theta}(x, x')$ .

Let  $x, x' \in B_0$ . Assume that  $x \in D_1$  and  $x' \in D_2$ . Let  $m \in [x, x']_{B_0} \cap D_1 \cap D_2$ . Then  $d_{\theta'}(x, x') \leq d_{\theta'}(x, m) + d_{\theta'}(m, x') \leq \ell_0 \ell_1 (d_{\theta}(x, m) + d_{\theta}(m, x'))$ . By Lemma 4.6 (1),  $d_{\theta}(x, m) + d_{\theta}(m, x') = d_{\theta}(x, x')$  and the lemma follows. □

**Lemma 4.14.** *Let  $(X, d_X)$  be a metric space,  $f : (\mathcal{I}, d_{\theta}) \rightarrow (X, d_X)$  be a map and  $k \in \mathbb{R}_+$ . Then  $f$  is  $k$ -Lipschitz continuous if and only if for every apartment  $A$  containing  $\mathfrak{s}$ ,  $f|_A$  is  $k$ -Lipschitz continuous.*

*Proof.* One implication is clear. Assume that for every apartment  $A$  containing  $\mathfrak{s}$ ,  $f|_A$  is  $k$ -Lipschitz continuous. Let  $x, x' \in \mathcal{I}$  and  $A_x, A_{x'}$  be apartments containing  $x + \mathfrak{s}$  and  $x' + \mathfrak{s}$ . Let  $(u, u') \in U_{\mathfrak{s}}(x, x')$  be such that  $|u| + |u'| = d_{\theta}(x, x')$ , which exists by Lemma 4.8. Then  $x +_{\mathfrak{s}} u \in A_x$  and  $x' +_{\mathfrak{s}} u' \in A_{x'}$ . One has

$$d_X(f(x), f(x')) \leq d_X(f(x), f(x +_{\mathfrak{s}} u)) + d_X(f(x' +_{\mathfrak{s}} u'), f(x')) \leq k(|u| + |u'|) \leq k d_{\theta}(x, x').$$

□

**Lemma 4.15.** *One has  $d_{\theta'} \leq \ell_0 \ell_1 d_{\theta}$ .*

*Proof.* By Lemma 4.14, Lemma 4.11 and Lemma 4.13,  $\text{Id} : (\mathcal{I}, d_{\theta}) \rightarrow (\mathcal{I}, d_{\theta'})$  is  $\ell_0 \ell_1$ -Lipschitz continuous, which proves the lemma. □

**Theorem 4.16.** *Let  $\theta_1, \theta_2 \in \Theta_+$ . Then  $d_{\theta_1}$  and  $d_{\theta_2}$  are equivalent.*

*Proof.* For  $i \in \{1, 2\}$ , write  $\theta_i = (|\cdot|_i, \mathfrak{s}_i)$ . As all the norms on  $\mathbb{A}$  are equivalent, we may assume  $|\cdot|_1 = |\cdot|_2 = |\cdot|$ . Let  $\mathfrak{t}^0 = \mathfrak{s}_1, \dots, \mathfrak{t}^n = \mathfrak{s}_2$  be a gallery between  $\mathfrak{s}_1$  and  $\mathfrak{s}_2$ . For  $i \in \llbracket 0, n \rrbracket$  set  $\theta^i = (|\cdot|, \mathfrak{t}^i)$ . By an induction using Lemma 4.15, there exists  $\ell \in \mathbb{R}_{>0}$  such that  $d_{\theta_1} = d_{\theta^0} \leq \ell d_{\theta^n} = K d_{\theta_2}$ . Theorem follows by symmetry. □

We thus obtain (at most) two topologies on  $\mathcal{I}$ : the topology  $\mathcal{T}_+$  induced by  $d_{\theta_+}$ , for any  $\theta_+ \in \Theta_+$  and the topology  $\mathcal{T}_-$  induced by  $d_{\theta_-}$ , for any  $\theta_- \in \Theta_-$ . We will see that when  $\mathcal{I}$  is not a building, these topologies are different (see Corollary 5.4).

**Corollary 4.17.** *Let  $A$  be an apartment of  $\mathcal{I}$ . Then the topology on  $A$  induced by  $\mathcal{T}_+$  is the affine topology on  $A$ .*

*Proof.* By Theorem 4.16, this topology is induced by  $d_{(| \cdot |, \mathfrak{t})}$  for some positive sector-germ  $\mathfrak{t}$  of  $A$ . Then Lemma 4.6 (1) concludes the proof.  $\square$

**Corollary 4.18.** *Let  $\rho$  be a retraction centered at a positive sector-germ,  $A = \rho(\mathcal{I})$ ,  $B$  be an apartment and  $d_A$  (resp.  $d_B$ ) be a distance on  $A$  (resp.  $B$ ) induced by a norm. Then:*

1. *for all  $\theta \in \Theta_+$ ,  $\rho : (\mathcal{I}, d_\theta) \rightarrow (A, d_A)$  is Lipschitz continuous,*
2. *the map  $\rho|_B : (B, d_B) \rightarrow (A, d_A)$  is Lipschitz continuous.*

*Proof.* By Theorem 4.16 we may assume  $\theta = (| \cdot |, \mathfrak{t})$ , where  $\mathfrak{t}$  is the center of  $\rho$ . Then by Lemma 4.6 (3),  $\rho : (\mathcal{I}, d_\theta) \rightarrow (A, d_\theta)$  is Lipschitz continuous and Lemma 4.6 (1) completes the proof.  $\square$

**Corollary 4.19.** *Let  $A, B$  be two apartments of  $\mathcal{I}$ . Then  $A \cap B$  is a closed subset of  $A$  (seen as an affine space).*

*Proof.* By Lemma 3.11,  $A$  and  $B$  are closed for  $\mathcal{T}_+$  and thus  $A \cap B$  is closed for  $\mathcal{T}_+$ . Consequently it is closed for the topology induced by  $\mathcal{T}_+$  on  $A$ , and Corollary 4.17 completes the proof.  $\square$

**Remark 4.20.** *Suppose that  $\mathcal{I}$  is not a building. Then by Subsection 3.3, for all  $\theta_+ \in \Theta_+$ ,  $(\mathcal{I}, d_{\theta_+})$  is not complete.*

Let  $\mathfrak{s}''$  be a positive sector-germ of  $\mathcal{I}$ ,  $\theta_+ = (| \cdot |, \mathfrak{s}'')$  and  $(S_n)$  be an increasing sequence of sectors with the germ  $\mathfrak{s}''$ . One says that  $(S_n)$  is converging if there exists a retraction onto an apartment  $\rho : \mathcal{I} \xrightarrow{\mathfrak{s}''} \rho(\mathcal{I})$  such that  $(\rho(x_n))$  converges, where  $x_n$  is the base point of  $S_n$  for all  $n \in \mathbb{N}$  and we call limit of  $(S_n)$  the set  $\bigcup_{n \in \mathbb{N}} S_n$ . One can show that the non-completeness of  $(\mathcal{I}, d_\theta)$  implies the existence of a converging sequence of the direction  $\mathfrak{s}''$  whose limit is not a sector of  $\mathcal{I}$ . To prove this one can associate to each Cauchy sequence  $(x_n)$  a sequence  $(x'_n)$  such that  $d_{\theta_+}(x'_n, x_n) \rightarrow 0$  and such that  $x'_n + \mathfrak{s}'' \subset x'_{n+1} + \mathfrak{s}''$  for all  $n \in \mathbb{N}$ . Then we show that  $(x'_n)$  converges in  $(\mathcal{I}, d_\theta)$  if, and only if the limit of  $(x'_n + \mathfrak{s}'')$  is a sector of  $\mathcal{I}$ .

## 4.6 Study of the action of $G$

In this subsection, we show that for every  $g \in G$ , the induced map  $g : \mathcal{I} \rightarrow \mathcal{I}$  is Lipschitz continuous for the distances of positive type.

**Lemma 4.21.** *Let  $g \in G$  and  $\mathfrak{s}$  be a sector-germ of  $\mathcal{I}$ . Then for every  $x \in \mathcal{I}$  and  $u \in \overline{C_f^v}$ ,  $g.(x +_{\mathfrak{s}} u) = g.x +_{g.\mathfrak{s}} u$ .*

*Proof.* Let  $x \in \mathcal{I}$  and  $u \in \overline{C_f^v}$ . Let  $A$  be an apartment containing  $x + \mathfrak{s}$ . Let  $A' = g.A$ . Then  $A'$  contains  $\mathfrak{s}' = g.\mathfrak{s}$ . Let  $\psi : \mathbb{A} \rightarrow A$  be an isomorphism such that  $\psi(+\infty) = \mathfrak{s}$ . Let  $f : A \rightarrow A'$  be the isomorphism induced by  $g$ . Set  $\psi' = f \circ \psi$ . Then  $\psi'(+\infty) = \mathfrak{s}'$ .

As  $x +_{\mathfrak{s}} u \in A$ ,

$$g.(x +_{\mathfrak{s}} u) = f(x +_{\mathfrak{s}} u) = f \circ \psi(\psi^{-1}(x) + u) = \psi'(\psi^{-1} \circ f^{-1}(f(x)) + u) = g.x +_{g.\mathfrak{s}} u.$$

$\square$

**Theorem 4.22.** *Let  $g \in G$  and  $\theta \in \Theta_+$ . Then  $g : (\mathcal{I}, d_\theta) \rightarrow (\mathcal{I}, d_\theta)$  is Lipschitz continuous.*

*Proof.* Write  $\theta = (|\cdot|, \mathfrak{s})$ . Let  $\theta' = (|\cdot|, g.\mathfrak{s})$ . By Theorem 4.16, it suffices to prove that  $g : (\mathcal{I}, d_\theta) \rightarrow (\mathcal{I}, d_{\theta'})$  is Lipschitz continuous.

Let  $x, x' \in \mathcal{I}$ . By Lemma 4.21,  $U_{g.\mathfrak{s}}(g.x, g.x') \supset U_{\mathfrak{s}}(x, x')$ , thus  $d_{\theta'}(g.x, g.x') \leq d_\theta(x, x')$ , which proves the theorem.  $\square$

## 4.7 Case of a building

In this subsection we assume that  $\mathcal{I}$  is a building. We show that the distances of positive type are equivalent to the usual distance.

Let  $d_{\mathbb{A}}$  be a distance on  $\mathbb{A}$  induced by some  $W^v$ -invariant euclidean norm  $|\cdot|$  on  $\mathbb{A}$ . Let  $x, x' \in \mathcal{I}$ ,  $A$  be an apartment containing  $x, x'$  and  $f : A \rightarrow \mathbb{A}$  be an isomorphism of apartments. One sets  $d_{\mathcal{I}}(x, x') = d_{\mathbb{A}}(f(x), f(x'))$ . Then  $d_{\mathcal{I}} : \mathcal{I} \rightarrow \mathbb{R}_+$  is well defined and is a distance on  $\mathcal{I}$  (see [Bro89] VI.3 for example). Recall that  $\rho_{+\infty} : \mathcal{I} \xrightarrow{+\infty} \mathbb{A}$ .

**Proposition 4.23.** *Let  $\theta \in \Theta_+$ . Then  $d_{\mathcal{I}}$  and  $d_\theta$  are equivalent.*

*Proof.* By Theorem 4.16, one can assume that  $\theta = (|\cdot|, +\infty)$ . Let  $k, \ell \in \mathbb{R}_{>0}$  be such that  $kd_{\mathcal{I}|\mathbb{A}^2} \leq d_{\theta|\mathbb{A}^2} \leq \ell d_{\mathcal{I}|\mathbb{A}^2}$ , which exists by Lemma 4.6 (1). Let us first show that  $\text{Id} : (\mathcal{I}, d_\theta) \rightarrow (\mathcal{I}, d_{\mathcal{I}})$  is  $\frac{1}{k}$ -Lipschitz continuous.

Let  $A$  be an apartment containing  $+\infty$ . Let  $x, x' \in A$ . Then by Lemma 4.6 (4) and the fact that the restriction of  $\rho_{+\infty}$  to  $A$  is an isometry for  $d_{\mathcal{I}}$ ,  $d_\theta(x, x') = d_\theta(\rho_{+\infty}(x), \rho_{+\infty}(x')) \geq kd_{\mathcal{I}}(\rho_{+\infty}(x), \rho_{+\infty}(x')) = kd_{\mathcal{I}}(x, x')$ . From Lemma 4.14 we deduce that  $\text{Id} : (\mathcal{I}, d_\theta) \rightarrow (\mathcal{I}, d_{\mathcal{I}})$  is  $\frac{1}{k}$ -Lipschitz continuous.

Let  $x, x' \in \mathcal{I}$ . By Corollary 3.8 there exist  $n \in \mathbb{N}_{>0}$  and  $x_0 = x, x_1, \dots, x_n = x' \in [x, x']$  such that  $[x, x'] = \bigcup_{i=0}^{n-1} [x_i, x_{i+1}]$  and such that  $[x_i, x_{i+1}] \cup +\infty$  is contained in an apartment for all  $i \in \llbracket 0, n-1 \rrbracket$ . By Lemma 4.6 (4),

$$\begin{aligned} d_\theta(x, x') &\leq \sum_{i=0}^{n-1} d_\theta(x_i, x_{i+1}) = \sum_{i=0}^{n-1} d_\theta(\rho_{+\infty}(x_i), \rho_{+\infty}(x_{i+1})) \\ &\leq \ell \sum_{i=0}^{n-1} d_{\mathcal{I}}(\rho_{+\infty}(x_i), \rho_{+\infty}(x_{i+1})) \\ &= \ell \sum_{i=0}^{n-1} d_{\mathcal{I}}(x_i, x_{i+1}) = \ell d_{\mathcal{I}}(x, x'), \end{aligned}$$

which proves the proposition.  $\square$

## 5 Mixed distances

In this section, we begin by proving that if  $\mathfrak{s}_-$  is a negative sector-germ, then every retraction centered at  $\mathfrak{s}_-$  is not continuous for  $\mathcal{T}_+$ , unless  $\mathcal{I}$  is a building. This implies that  $\mathcal{T}_+ \neq \mathcal{T}_-$  and motivates the introduction of mixed distances, which are sums of a distance of positive type with a distance of negative type. We then study them.

## 5.1 Comparison of positive and negative topologies

In this subsection, we show that  $\mathcal{T}_+$  and  $\mathcal{T}_-$  are different when  $\mathcal{I}$  is not a building. For this we prove that retractions centered at negative sector-germs are not continuous for  $\mathcal{T}_+$ . To prove this we show that the set of vertices  $\mathcal{I}_0$  is composed of limit points when  $\mathcal{I}$  is not a building and then we apply finiteness results of [Héb17].

Fix a norm  $|\cdot|$  on  $\mathbb{A}$ .

**Proposition 5.1.** *Let  $\theta \in \Theta$ . Then  $\mathcal{I}_0$  is discrete in  $(\mathcal{I}, d_\theta)$  if and only if  $\mathcal{I}$  is a building.*

*Proof.* Assume that  $\mathcal{I}$  is a building. By Proposition 4.23, we can replace  $d_\theta$  by a usual distance  $d_{\mathcal{I}}$  on  $\mathcal{I}$ . By Lemma 3.13,  $\mathcal{I}_0 \cap \mathbb{A} = Y$ , which is a lattice in  $\mathbb{A}$ . Let  $\eta > 0$  be such that for all  $\lambda, \lambda' \in Y$ ,  $d_{\mathcal{I}}(\lambda, \lambda') < \eta$  implies  $\lambda = \lambda'$ . Let  $\lambda, \lambda' \in \mathcal{I}_0$  be such that  $d_{\mathcal{I}}(\lambda, \lambda') < \eta$ . Let  $A$  be an apartment of  $\mathcal{I}$  containing  $\lambda$  and  $\lambda'$  and  $g \in G$  be such that  $g.A = \mathbb{A}$ . Then  $d_{\mathcal{I}}(g.\lambda, g.\lambda') = d_{\mathcal{I}}(\lambda, \lambda') < \eta$ , thus  $\lambda = \lambda'$  and hence  $\mathcal{I}_0$  is discrete in  $\mathcal{I}$ .

Assume now that  $\mathcal{I}$  is not a building and thus that  $W^v$  is infinite. By Theorem 4.16, one can suppose that  $\theta = (|\cdot|, +\infty)$ . Let  $\epsilon > 0$ . Let us show that there exists  $\lambda \in \mathcal{I}_0$  such that  $d_\theta(\lambda, 0) < 2\epsilon$  and  $\lambda \neq 0$ . Let  $M_0$  be a wall of  $\mathbb{A}$  containing 0 such that for all consecutive walls  $M_1$  and  $M_2$  of the direction  $M_0$ ,  $d_\theta(M_1, M_2) < \epsilon$  (such a direction exists by Proposition 2.1 (2)). Let  $M$  be a wall such that  $d_\theta(0, M) < \epsilon$  and such that  $0 \notin D$ , where  $D$  is the half-apartment of  $\mathbb{A}$  delimited by  $M$  and containing  $+\infty$ . By Lemma 3.9, there exists an apartment  $A$  such that  $A \cap \mathbb{A} = D$ . Let  $\phi : \mathbb{A} \xrightarrow{A \cap \mathbb{A}} A$  and  $\mu = \phi(0)$ . Let  $x \in M$  be such that  $d_\theta(0, x) < \epsilon$ . Then by Lemma 4.6 (4),  $d_\theta(\lambda, x) = d_\theta(0, x)$  and thus  $d(\lambda, 0) < 2\epsilon$ . As  $\lambda \notin \mathbb{A}$ ,  $\lambda \neq 0$  and we get the proposition.  $\square$

**Remark 5.2.** *In fact, by Theorem 4.22, we proved that when  $\mathcal{I}$  is not a building, every point of  $\mathcal{I}_0$  is a limit point.*

If  $B$  is an apartment and  $(x_n) \in B^\mathbb{N}$ , one says that  $(x_n)$  converges towards  $\infty$ , if for some isomorphism  $f : B \rightarrow \mathbb{A}$ ,  $|f(x_n)| \rightarrow +\infty$ .

**Proposition 5.3.** *Assume that  $\mathcal{I}$  is not a building. Let  $\mathfrak{s}_-$  be a negative sector-germ of  $\mathcal{I}$  and  $\theta \in \Theta_+$ . Equip  $\mathcal{I}$  with  $d_\theta$ . Let  $\rho_-$  be a retraction centered at  $\mathfrak{s}_-$  and  $(\lambda_n) \in \mathcal{I}_0^\mathbb{N}$  be an injective and converging sequence. Then  $\rho_-(\lambda_n) \rightarrow \infty$  in  $\rho_-(\mathcal{I})$ . In particular  $\rho_-$  is not continuous.*

*Proof.* Let  $A = \rho_-(\mathcal{I})$  and  $\mathfrak{s}_+$  be the sector-germ of  $A$  opposite to  $\mathfrak{s}_-$ . Using Theorem 4.16, we may assume that  $\theta = (|\cdot|, \mathfrak{s}_+)$ . Let  $\rho_+ : \mathcal{I} \xrightarrow{\mathfrak{s}_+} A$ . Let  $\lambda = \lim \lambda_n$  and  $\mu = \rho_+(\lambda)$ . Then by Corollary 4.18,  $\rho_+(\lambda_n) \rightarrow \mu$ . Let  $Y_A = \mathcal{I}_0 \cap A$ . Then  $Y_A$  is a lattice in  $A$  by Lemma 3.13. As  $\rho_+(\lambda_n) \in Y_A$  for all  $n \in \mathbb{N}$ ,  $\rho_+(\lambda_n) = \mu$  for  $n$  large enough.

For all  $n \in \mathbb{N}$ ,  $\rho_-(\lambda_n) \in Y_A$ . By Theorem 5.6 of [Héb17], for all  $\lambda' \in Y_A$ ,  $\rho_+^{-1}(\{\lambda'\}) \cap \rho_-^{-1}(\{\mu\})$  is finite, and the proposition follows.  $\square$

**Corollary 5.4.** *If  $\mathcal{I}$  is not a building,  $\mathcal{T}_+$  and  $\mathcal{T}_-$  are different.*

**Remark 5.5.** *Proposition 5.3 shows that if  $\theta, \theta' \in \Theta$  have opposite signs, then every open subset of  $(\mathcal{I}, d_\theta)$  containing a point of  $\mathcal{I}_0$  is not bounded for  $d_{\theta'}$ .*

## 5.2 Mixed distances

In this section we define and study mixed distances.

Let  $\Xi = \Theta_+ \times \Theta_-$ . Let  $\xi = (\theta_+, \theta_-) \in \Xi$ . Set  $d_\xi = d_{\theta_+} + d_{\theta_-}$ .

**Theorem 5.6.** *Let  $\xi \in \Xi$ . We equip  $\mathcal{I}$  with  $d_\xi$ . Then:*



1. For all  $\xi' \in \Xi$ ,  $d_\xi$  and  $d_{\xi'}$  are equivalent.
2. For all  $g \in G$ , the induced map  $g : \mathcal{I} \rightarrow \mathcal{I}$  is Lipschitz-continuous.
3. The topology induced on every apartment is the affine topology.
4. Every retraction of  $\mathcal{I}$  centered at a sector-germ is Lipschitz continuous.
5. The set  $\mathcal{I}_0$  is discrete.

*Proof.* The assertions 1 to 4 are consequences of Theorem 4.16, Theorem 4.22, Corollary 4.17 and Corollary 4.18. Let us prove (5). Let  $\lambda \in \mathcal{I}_0$  and set  $\lambda_+ = \rho_{+\infty}(\lambda)$  and  $\lambda_- = \rho_{-\infty}(\lambda)$ . By Theorem 5.6 of [Héb17],  $\rho_{+\infty}^{-1}(\{\lambda_+\}) \cap \rho_{-\infty}^{-1}(\{\lambda_-\})$  is finite and thus there exists  $r > 0$  such that  $B(\lambda, r) \cap \rho_{+\infty}^{-1}(\{\lambda_+\}) \cap \rho_{-\infty}^{-1}(\{\lambda_-\}) = \{\lambda\}$ , where  $B(\lambda, r)$  is the open ball of the radius  $r$  and the center  $\lambda$ . Let  $k \in \mathbb{R}_{>0}$  be such that  $\rho_{+\infty}$  and  $\rho_{-\infty}$  are  $k$ -Lipschitz continuous. Let  $\eta > 0$  be such that for all  $\mu, \mu' \in Y$ ,  $\mu \neq \mu'$  implies  $d_\xi(\mu, \mu') \geq \eta$ . Let  $r' = \min(r, \frac{\eta}{k})$ . Let us prove that  $B(\lambda, r') \cap \mathcal{I}_0 = \{\lambda\}$ . Let  $\mu \in B(\lambda, r') \cap \mathcal{I}_0$ . Suppose  $\rho_{\sigma\infty}(\mu) \neq \lambda_\sigma$ , for some  $\sigma \in \{-, +\}$ . Then

$$kd_\xi(\mu, \lambda) \geq d_\xi(\rho_{\sigma\infty}(\mu), \rho_{\sigma\infty}(\lambda)) \geq \eta,$$

thus  $\lambda \notin B(\lambda, r')$ , a contradiction. Therefore  $\rho_{+\infty}(\mu) = \lambda_+$  and  $\rho_{-\infty}(\mu) = \lambda_-$ , hence  $\lambda = \mu$  by choice of  $r$ , which completes the proof of the theorem.  $\square$

We denote by  $\mathcal{T}_m$  the topology on  $\mathcal{I}$  induced by any  $d_\xi$ ,  $\xi \in \Xi$ .

### 5.3 Link with the initial topology with respect to the retractions

In this subsection, we prove that the topology  $\mathcal{T}_m$  agrees with the initial topology with respect to the family of retractions centered at sector-germs (see Corollary 5.10). For this, we introduce for all  $u \in C_f^v$  a map  $T_u : \mathcal{I} \rightarrow \mathbb{R}_+$  which, for each  $x \in \mathcal{I}$ , measures the distance along the ray  $x + (\mathbb{R}_+ u)_\infty$  between  $x \in \mathcal{I}$  and  $\mathbb{A}$ . We then use the fact that for all  $\lambda \in Y \cap C_f^v$ ,  $T_\lambda \leq \ell(\rho_{+\infty} - \rho_{-\infty})$ , for some  $\ell \in \mathbb{R}_+$  (see Lemma 5.7).

Fix a norm  $|\cdot|$  on  $\mathbb{A}$ .

#### Definition of $y_u$ and $T_u$

We now review briefly the results of the paragraph “Definition of  $y_\nu$  and  $T_\nu$ ” of Section 3 of [Héb17]. Let  $u \in C_f^v$  and  $\sigma \in \{-, +\}$ . Let  $\delta_+ = \mathbb{R}_+ u \subset \mathbb{A}$  and  $\delta_- = \mathbb{R}_- u \subset \mathbb{A}$ . Then  $\delta_+$  and  $\delta_-$  are generic rays. Let  $x \in \mathcal{I}$ , then there exists a unique  $y_{\sigma u}(x) \in \mathbb{A}$  such that  $x + \delta_{\sigma\infty} \cap \mathbb{A} = y_{\sigma u}(x) + \sigma \mathbb{R}_+ u \subset \mathbb{A}$  and there exists a unique  $T_{\sigma u}(x) \in \mathbb{R}_+$  such that

$$y_{\sigma u}(x) = x + \sigma_{\infty} T_{\sigma u}(x).u = \rho_{\sigma\infty}(x) + \sigma T_{\sigma u}(x).u.$$

Then for all  $x \in \mathcal{I}$ ,  $x \in \mathbb{A}$  if and only if  $y_u(x) = x$  if and only if  $T_u(x) = 0$ .

**Lemma 5.7.** *Let  $\lambda \in Y \cap C_f^v$ . Then there exists  $\ell_{|\cdot|} \in \mathbb{R}_{>0}$  such that for all  $x \in \mathcal{I}$ ,*

$$T_\lambda(x), T_{-\lambda}(x) \leq \ell_{|\cdot|} |\rho_{+\infty}(x) - \rho_{-\infty}(x)|.$$

*Proof.* By Corollary 4.2 and Remark 4.3 of [Héb17], there exists a linear map  $h : \mathbb{A} \rightarrow \mathbb{R}$  such that  $T_\lambda(x), T_{-\lambda}(x) \leq h(\rho_{-\infty}(x) - \rho_{+\infty}(x))$  for all  $x \in \mathcal{I}$ , which proves the existence of  $\ell_{|\cdot|}$ .  $\square$

**Lemma 5.8.** *Let  $\xi \in \Xi$  and  $a \in \mathcal{I}$ . Let  $A$  be an apartment containing  $a$ . Let  $\mathfrak{s}_-, \mathfrak{s}_+$  be two opposite sector-germs of  $A$  and  $\rho_+ : \mathcal{I} \xrightarrow{\mathfrak{s}_+} A$ ,  $\rho_- : \mathcal{I} \xrightarrow{\mathfrak{s}_-} A$ . Then there exists  $k \in \mathbb{R}_{>0}$  such that for all  $x \in \mathcal{I}$ ,  $d_\xi(a, x) \leq k(d_\xi(a, \rho_-(x)) + d_\xi(a, \rho_+(x)))$ .*

*Proof.* Using isomorphisms of apartments, we may assume  $A = \mathbb{A}$ ,  $\mathfrak{s}_+ = +\infty$  and  $\mathfrak{s}_- = -\infty$ . By Theorem 5.6 (1) we may assume  $\xi = ((|\cdot|, \mathfrak{s}_+), (|\cdot|, \mathfrak{s}_-))$ .

Let  $\lambda \in C_f^v$ . Let  $T_+ = T_\lambda : \mathcal{I} \rightarrow \mathbb{R}_+$  and  $T_- = T_{-\lambda} : \mathcal{I} \rightarrow \mathbb{R}_+$ . By Lemma 5.7 and Lemma 4.6 (1), there exists  $\ell \in \mathbb{R}_{>0}$  such that  $T_\sigma(x) \leq \ell d_\xi(\rho_-(x), \rho_+(x))$  for all  $x \in \mathcal{I}$  and both  $\sigma \in \{-, +\}$ .

Set  $d_+ = d_{(|\cdot|, +\infty)}$  and  $d_- = d_{(|\cdot|, -\infty)}$ . Let  $x \in \mathcal{I}$  and  $\sigma \in \{-, +\}$ . One has  $x +_{\sigma\infty} T_\sigma(x)u = \rho_\sigma(x) + \sigma T_\sigma(x)u$ . Thus

$$\begin{aligned} d_\sigma(\rho_\sigma(x), x) &\leq 2T_\sigma(x)|u| \leq 2\ell|u|d_\sigma(\rho_-(x), \rho_+(x)) \\ &\leq 2\ell|u|(d_\sigma(\rho_-(x), a) + d_\sigma(\rho_+(x), a)). \end{aligned}$$

As  $d_\sigma(a, x) \leq d(a, \rho_\sigma(x)) + d(\rho_\sigma(x), x)$  we deduce that

$$d_\xi(a, x) = d_-(a, x) + d_+(a, x) \leq (4\ell|u| + 2)(d_\xi(a, \rho_-(x)) + d_\xi(a, \rho_+(x))).$$

□

**Corollary 5.9.** *Let  $\xi \in \Xi$ . Equip  $\mathcal{I}$  with  $d = d_\xi$ . Then if  $X \subset \mathcal{I}$  the following assertions are equivalent:*

1.  $X$  is bounded.
2. For every retraction  $\rho$  centered at a sector-germ of  $\mathcal{I}$ ,  $\rho(X)$  is bounded.
3. There exist two opposite sector-germs  $\mathfrak{s}_+$  and  $\mathfrak{s}_-$  such that if  $\rho_{\mathfrak{s}_-}$  and  $\rho_{\mathfrak{s}_+}$  are retractions centered at  $\mathfrak{s}_-$  and  $\mathfrak{s}_+$ ,  $\rho_{\mathfrak{s}_-}(X)$  and  $\rho_{\mathfrak{s}_+}(X)$  are bounded.

Moreover every bounded subset of  $\mathcal{I}_0$  is finite.

*Proof.* By Theorem 5.6, (1) implies (2) which clearly implies (3). The fact that (3) implies (1) is a consequence of Lemma 5.8. The last assertion is a consequence of (3) and of Theorem 5.6 of [Héb17]. □

**Corollary 5.10.** *The sets  $\rho_+^{-1}(V) \cap \rho_-^{-1}(V)$  such that  $V$  is an open set of an apartment  $A$  and  $\rho_-, \rho_+$  are retractions onto  $A$  centered at opposite sector-germs of  $A$  form a basis of  $\mathcal{T}_m$ . In particular  $\mathcal{T}_m$  is the initial topology with respect to the retractions centered at sector-germs.*

*Proof.* This is a consequence of Lemma 5.8. □

## 5.4 A continuity property for the map $+_{+\infty}$

The aim of this subsection is to prove the theorem below, which will be useful to prove the contractibility of  $\mathcal{I}$  for  $\mathcal{T}_m$ . To simplify the notation, we write  $+$  instead of  $+_{+\infty}$ .

**Theorem 5.11.** *Let  $\xi \in \Xi$  and  $u \in C_f^v$ . Equip  $\mathcal{I}$  with  $d_\xi$ . Then the map  $\mathcal{I} \times \mathbb{R}_+ \rightarrow \mathcal{I}$  defined by  $(x, t) \mapsto x + tu$  is continuous.*

To prove this theorem we prove that if a sequence  $((x_n), (t_n)) \in (\mathcal{I} \times \mathbb{R}_+)^{\mathbb{N}}$  converges towards some  $(x, t) \in \mathcal{I} \times \mathbb{R}_+$ , then  $(x_n + t_n u)$  converges towards  $x + tu$ . We first treat the case where  $t \neq 0$ .

Fix  $\xi \in \Xi$  and write  $\xi = (\theta_+, \theta_-)$ . Fix a norm  $|\cdot|$  on  $\mathbb{A}$ .

**Lemma 5.12.** *Let  $u \in C_f^v$ . Then  $T_u : \mathcal{I} \rightarrow \mathbb{R}_+$  and  $y_u : \mathcal{I} \rightarrow (\mathbb{A}, |\cdot|)$  are Lipschitz continuous for  $d_{\theta_+}$  and  $d_\xi$ .*

*Proof.* By Theorem 4.16 and Theorem 5.6, we can assume  $\theta_+ = (+\infty, |\cdot|)$ . Let  $\ell \in \mathbb{R}_{>0}$  be such that for all  $a \in \mathbb{A}$ ,  $\ell|a|u - a \in C_f^v$ . Let  $x, x' \in \mathcal{I}$  and  $(u, u') \in U_{+\infty}(x, x')$  be such that  $d_{\theta_+}(x, x') = |u| + |u'|$ , which exists by Lemma 4.8. Then  $x + T_u(x)u \in \mathbb{A}$  and thus  $x' + u' + T_u(x)u = x + u + T_u(x)u \in \mathbb{A}$ . Therefore

$$x' + u' + T_u(x)u + (\ell|u'|u - u') = x' + (T_u(x) + \ell|u'|)u \in \mathbb{A}.$$

Hence  $T_u(x') \leq T_u(x) + \ell|u'| \leq T_u(x) + \ell d_{\theta_+}(x, x')$ . By symmetry we deduce that  $T_u$  is  $\ell$ -Lipschitz continuous for  $d_{\theta_+}$ . The fact that  $y_u$  is Lipschitz continuous for  $d_{\theta_+}$  is a consequence of the continuity of the map  $+$  (Lemma 4.7) and of the fact that  $y_u = \rho_{+\infty} + T_u \cdot u$ . As  $d_{\theta_+} \leq d_\xi$ , the lemma is proved.  $\square$

**Lemma 5.13.** *Let  $u \in C_f^v$  and  $(x_n, t_n) \in \mathcal{I} \times \mathbb{R}_{>0}$  be such that  $x_n \rightarrow x$  for  $d_\xi$  and  $t_n \rightarrow t$ , for some  $x \in \mathcal{I}$  and  $t \in \mathbb{R}_{>0}$ . Then  $x_n + t_n u \rightarrow x + tu$  for  $d_\xi$ .*

*Proof.* First assume  $x \in \mathbb{A}$ . By Lemma 5.12,  $T_u(x_n) \rightarrow T_u(x) = 0$ . Consequently, for  $n \in \mathbb{N}$  large enough,  $x_n + t_n u \in \mathbb{A}$ . Write  $\xi = (\theta_+, \theta_-)$ . By the continuity of the map  $+$  for  $d_{\theta_+}$  (Lemma 4.7),  $x_n + t_n u \rightarrow x + tu$  for  $d_{\theta_+}$ . As the topologies induced by  $d_{\theta_+}$  and  $d_\xi$  on  $\mathbb{A}$  agree with the topology induced by its structure of a finite-dimensional real vector-space (by Corollary 4.17 and Theorem 5.6 (3)), we deduce that  $x_n + u \rightarrow x + u$  for  $d_\xi$ .

We no more assume that  $x \in \mathbb{A}$ . Let  $A$  be an apartment containing  $x + \infty$ . Let  $\phi : A \xrightarrow{+\infty} \mathbb{A}$ . Let  $g \in G$  be an automorphism inducing  $\phi$ . By Lemma 4.21,  $x_n + t_n u = g^{-1} \cdot (g \cdot (x_n + t_n u)) = g^{-1} \cdot (g \cdot x_n + t_n u)$  for all  $n \in \mathbb{N}$ . As  $g \cdot x \in \mathbb{A}$ , we deduce that  $g \cdot x_n + t_n u \rightarrow g \cdot x + tu$  for  $d_\xi$ . By the continuity of  $g^{-1} : (\mathcal{I}, d_\xi) \rightarrow (\mathcal{I}, d_\xi)$  (by Theorem 5.6 (2)),  $x_n + u \rightarrow x + u$  for  $d_\xi$ .  $\square$

It remains to prove that if a sequence  $(x_n, t_n) \in (\mathcal{I} \times \mathbb{R}_+)$  converges towards  $(x, 0)$ , for some  $x \in \mathcal{I}$ , then  $(x_n + t_n u)$  converges towards  $x$ . In order to prove this we first study the map  $t \mapsto \rho_{-\infty}(x + tu)$ .

## Tits preorder on $\mathcal{I}$ , vectorial distance on $\mathcal{I}$ and paths

Recall the definition of the Tits preorder  $\leq$  on  $\mathbb{A}$  from Subsection 2.2. As  $\leq$  is invariant under the action of the Weyl group  $W^v$ ,  $\leq$  induces a preorder  $\leq_A$  on every apartment  $A$ . Let  $A$  be an apartment and  $x, y \in A$  be such that  $x \leq_A y$ . Then by Proposition 5.4 of [Rou11], if  $A'$  is an apartment containing  $x, y$ ,  $x \leq_{A'} y$ . This enables to define the following relation  $\leq$  on  $\mathcal{I}$ : if  $x, y \in \mathcal{I}$ , one says that  $x \leq y$  if there exists an apartment  $A$  containing  $x, y$  and such that  $x \leq_A y$ . By Théorème 5.9 of [Rou11], this defines a preorder on  $\mathcal{I}$  and one calls  $\leq$  the *Tits preorder*.

Let  $x, x' \in \mathcal{I}$  be such that  $x \leq x'$ . Let  $A$  be an apartment containing  $x, x'$  and  $f : A \rightarrow \mathbb{A}$  be an isomorphism of apartments. Then  $f(x') - f(x)$  is in the Tits cone  $\mathcal{T}$ . Therefore there exists a unique  $d^v(x, x')$  in  $\overline{C_f^v} \cap W^v \cdot (f(x') - f(x))$ . One calls  $d^v$  the *vectorial distance*.

Let  $u \in \overline{C_f^v}$ . A  $u$ -path is a piecewise linear continuous map  $\pi : [0, 1] \rightarrow \mathbb{A}$  such that each (existing) tangent vector  $\pi'(t)$  belongs to  $W^v \cdot u$ . Let  $x, x' \in \mathcal{I}$  be such that  $x \leq x'$ ,

$A$  be an apartment containing them and  $f : \mathbb{A} \rightarrow A$ . We define  $\pi_{x,x'} : [0, 1] \rightarrow \mathcal{I}$  by  $t \mapsto f((1-t)f^{-1}(x) + tf^{-1}(x'))$ . By Proposition 5.4 of [Rou11],  $\pi_{x,x'}$  does not depend on the choice of  $A$ .

Let  $x \in \mathcal{I}$  and  $u \in \overline{C_f^v}$ . Then  $d^v(x, x+u) = u$ .

**Lemma 5.14.** *Let  $x \in \mathcal{I}$  and  $u \in \overline{C_f^v}$ . Then  $\rho_{-\infty} \circ \pi_{x,x+u}$  is a  $u$ -path.*

*Proof.* This is a weak version of Theorem 6.2 of [GR08] (a Hecke path of the shape  $u$  is a  $u$ -path satisfying some conditions, see Section 5 of [GR08] for the definition).  $\square$

Recall that the  $\alpha_i^\vee$ , for  $i \in I$ , denote the simple roots. Let  $Q_{\mathbb{R}_+}^\vee = \bigoplus_{i \in I} \mathbb{R}_+ \alpha_i^\vee \subset \mathbb{A}$ .

**Lemma 5.15.** *Let  $u \in \overline{C_f^v}$  and  $\pi : [0, 1] \rightarrow \mathbb{A}$  be a  $u$ -path. Then  $\pi(1) - \pi(0) - u \in Q_{\mathbb{R}_+}^\vee$ .*

*Proof.* Let  $w \in W^v$ . Then by Proposition 3.12 d) of [Kac94],  $w.u - u \in -Q_{\mathbb{R}_+}^\vee$ . Thus for all  $t$  such that  $\pi'(t)$  is defined,  $\pi'(t) - u \in -Q_{\mathbb{R}_+}^\vee$  and the lemma follows.  $\square$

Let  $|\cdot|_0$  be a norm on  $\mathbb{A}$  such that for all  $q = \sum_{i \in I} q_i \alpha_i^\vee \in \bigoplus_{i \in I} \mathbb{R} \alpha_i^\vee$ ,  $|q|_0 = \sum_{i \in I} |q_i|$ .

**Lemma 5.16.** *Let  $x \in \mathcal{I}$ ,  $u \in \overline{C_f^v}$  and  $t, t' \in \mathbb{R}_+$  be such that  $t \leq t'$ . Then*

$$|\rho_{-\infty}(x+tu) - \rho_{-\infty}(x)|_0 \leq (t+t')|u|_0 + |\rho_{-\infty}(x+t'u) - \rho_{-\infty}(x)|_0.$$

*Proof.* Write  $\rho_{-\infty}(x+tu) - \rho_{-\infty}(x) = tu - q_1$  and  $\rho_{-\infty}(x+t'u) - \rho_{-\infty}(x+tu) = (t'-t)u - q_2$ , with  $q_1, q_2 \in Q_{\mathbb{R}_+}^\vee$ , which is possible by Lemma 5.14 and Lemma 5.15. Then  $\rho_{-\infty}(x+t'u) - \rho_{-\infty}(x) = t'u - q_1 - q_2$ . One has  $|\rho_{-\infty}(x+tu) - \rho_{-\infty}(x)|_0 \leq t|u|_0 + |q_1|_0$ . By choice of  $|\cdot|_0$ ,  $|q_1|_0 \leq |q_1 + q_2|_0 = |\rho_{-\infty}(x+t'u) - \rho_{-\infty}(x) - t'u|_0$ , and the lemma follows.  $\square$

The following lemma completes the proof of Theorem 5.11.

**Lemma 5.17.** *Let  $u \in C_f^v$ . Let  $(x_n) \in \mathcal{I}^\mathbb{N}$  and  $(t_n) \in \mathbb{R}_+^\mathbb{N}$  be such that  $(x_n)$  converges for  $d_\xi$  and  $(t_n)$  converges towards 0. Then  $(x_n + t_n u)$  converges towards  $\lim x_n$  for  $d_\xi$ .*

*Proof.* By Theorem 5.6, we can assume  $\xi = (|\cdot|_0, +\infty), (|\cdot|_0, -\infty)$ . Let  $x = \lim x_n$ . By the same reasoning as in the proof of Lemma 5.13:

- we can assume  $x \in \mathbb{A}$ ,
- $x_n + (T_u(x_n) + t_n)u \rightarrow x$ .

By Lemma 5.16, for all  $n \in \mathbb{N}$ ,

$$|\rho_{-\infty}(x_n + t_n u) - \rho_{-\infty}(x_n)|_0 \leq |\rho_{-\infty}(x_n + (T_u(x_n) + t_n)u) - \rho_{-\infty}(x)|_0 + (T_u(x_n) + 2t_n)|u|_0,$$

and thus  $\rho_{-\infty}(x_n + t_n u) \rightarrow \rho_{-\infty}(x)$ .

By continuity of the map  $+$  (Lemma 4.7) and the continuity of  $\rho_{+\infty}$  (Corollary 4.18) for  $d_{\theta_+}$ ,  $\rho_{+\infty}(x_n + t_n u) \rightarrow \rho_{+\infty}(x)$ . Using Lemma 5.8 we deduce that  $(x_n + t_n u)$  converges towards  $x$ , which is the desired conclusion.  $\square$

## 6 Contractibility of $\mathcal{I}$

In this section we prove the contractibility of  $\mathcal{I}$  for  $\mathcal{T}_+$ ,  $\mathcal{T}_-$  and  $\mathcal{T}_m$ .

Let  $|\cdot|$  be a norm on  $\mathbb{A}$ ,  $\theta = (|\cdot|, +\infty)$  and  $\xi = ((|\cdot|, +\infty), (|\cdot|, -\infty))$ . To simplify the notation we write  $+$  instead of  $+\infty$ .

**Proposition 6.1.** *Let  $u \in C_f^v$ . We define  $\chi_u : \mathcal{I} \times [0, 1] \rightarrow \mathcal{I}$  by*

$$\begin{cases} \chi_u(x, t) = x + \frac{t}{1-t}u & \text{if } \frac{t}{1-t} < T_u(x) \\ \chi_u(x, t) = y_u(x) & \text{if } \frac{t}{1-t} \geq T_u(x), \end{cases}$$

where we set  $\frac{1}{1-t} = +\infty > t$  for all  $t \in \mathbb{R}$ . Then  $\chi_u$  is a strong deformation retract on  $\mathbb{A}$  for  $d_\theta$  and  $d_\xi$ .

*Proof.* Let  $x \in \mathbb{A}$  and  $t \in [0, 1]$ . Then  $T_u(x) = 0$  and thus  $\chi_u(x, t) = y_u(x) = x$ . Let  $x \in \mathcal{I}$ . Then  $\chi_u(x, 0) = x$  and  $\chi_u(x, 1) = y_u(x) \in \mathbb{A}$ . It remains to show that  $\chi_u$  is continuous for  $d_\theta$  and  $d_\xi$ . Let  $(x_n, t_n) \in (\mathcal{I} \times [0, 1])^\mathbb{N}$  be a converging sequence for  $d_\theta$  or  $d_\xi$  and  $(x, t) = \lim(x_n, t_n)$ . Suppose for example that  $\frac{t}{1-t} < T_u(x)$  (the case  $\frac{t}{1-t} = T_u(x)$  and  $\frac{t}{1-t} > T_u(x)$  are analogous). Then by the continuity of  $T_u$  (Lemma 5.12),  $\frac{t_n}{1-t_n} < T_u(x_n)$  for  $n$  large enough and thus by the continuity of the map  $+$  (Lemma 4.7 for  $d_\theta$  and Theorem 5.11 for  $d_\xi$ ),  $\chi_u(x_n, t_n) = x_n + \frac{t_n}{1-t_n}u \rightarrow x + \frac{t}{1-t}u = \chi_u(x, t)$ . Therefore,  $\chi_u$  is continuous, which concludes the proof.  $\square$

**Corollary 6.2.** *The measure  $\mathcal{I}$  is contractible for  $\mathcal{T}_+$ ,  $\mathcal{T}_-$  and  $\mathcal{T}_m$ .*

*Proof.* Let  $u \in C_f^v$ . We define  $\Upsilon_u : \mathcal{I} \times [0, 1] \rightarrow \mathcal{I}$  by

$$\begin{cases} \Upsilon_u(x, t) = \chi_u(x, 2t) & \text{if } t \leq \frac{1}{2} \\ \Upsilon_u(x, t) = 2(1-t)y_u(x) & \text{if } t > \frac{1}{2}. \end{cases}$$

Then  $\Upsilon_u$  is a strong deformation retract on  $\{0\}$  for  $d_\theta$  and  $d_\xi$ , which proves that  $(\mathcal{I}, \mathcal{T}_+)$  and  $(\mathcal{I}, \mathcal{T}_m)$  are contractible. By symmetry,  $(\mathcal{I}, \mathcal{T}_-)$  is contractible.  $\square$

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