arXiv:0706.0362v1 [math.OA] 4 Jun 2007

COVERINGS OF SKEW-PRODUCTS AND CROSSED PRODUCTS BY COACTIONS

DAVID PASK, JOHN QUIGG, AND AIDAN SIMS

Abstract. Consider a projective limit G of finite groups G_n. Fix a compatible family δ^n of coactions of the G_n on a C^*-algebra A. From this data we obtain a coaction δ of G on A. We show that the coaction crossed product of A by δ is isomorphic to a direct limit of the coaction crossed products of A by the δ^n.

If $A = C^*(\Lambda)$ for some k-graph Λ, and if the coactions δ^n correspond to skew-products of Λ, then we can say more. We prove that the coaction crossed-product of $C^*(\Lambda)$ by δ may be realised as a full corner of the C^*-algebra of a $(k+1)$-graph. We then explore connections with Yeend's topological higher-rank graphs and their C^*-algebras.

1. Introduction

In this article we investigate how certain coactions of discrete groups on k-graph C^*-algebras behave under inductive limits. This leads to interesting new connections between k-graph C^*-algebras, nonabelian duality, and Yeend's topological higher-rank graph C^*-algebras.

We consider a particularly tractable class of coactions of finite groups on k-graph C^*-algebras. A functor c from a k-graph Λ to a discrete group G gives rise to two natural constructions. At the level of k-graphs, one may construct the skew-product k-graph $\Lambda \times_c G$; and at the level of C^*-algebras, c induces a coaction δ of G on $C^*(\Lambda)$. It is a theorem of [15] that these two constructions are compatible in the sense that the k-graph algebra $C^*(\Lambda \times_c G)$ is canonically isomorphic to the coaction crossed-product C^*-algebra $C^*(\Lambda) \times_\delta G$.

The skew-product construction is also related to discrete topology: given a regular covering map from a k-graph Γ to a connected k-graph Λ, one obtains an isomorphism of Γ with a skew-product of Λ by a discrete group G [15, Theorem 6.11]. Further results of [15] then show how to realise the C^*-algebra of Γ as a coaction crossed product of the C^*-algebra of Λ.

The results of [12] investigate the relationship between $C^*(\Lambda)$ and $C^*(\Gamma)$ from a different point of view. Specifically, they show how a covering p of a k-graph Λ by a k-graph Γ induces an inclusion of $C^*(\Lambda)$ into $C^*(\Gamma)$. A sequence of compatible coverings therefore gives rise to an inductive limit of C^*-algebras. The main results

Date: June 3, 2007.

2000 *Mathematics Subject Classification.* Primary: 46L05; Secondary: 46L55.

Key words and phrases. C^*-algebra, coaction, covering, crossed-product, graph algebra, k-graph.

This research was supported by the ARC.

of [12] show how to realise this inductive limit as a full corner in the C^*-algebra of a $(k+1)$-graph.

We can combine the ideas discussed in the preceding three paragraphs as follows. Fix a k-graph Λ, a projective sequence of finite groups G_n, and a sequence of functors $c_n : \Lambda \to G_n$ which are compatible with the projective structure. We obtain from this data a sequence of skew-products $\Lambda \times_{c_n} G_n$ which form a sequence of compatible coverings of Λ. By results of [12], we therefore obtain an inductive system of k-graph C^*-algebras $C^*(\Lambda \times_{c_n} G_n)$. The results of [15] show that each $C^*(\Lambda \times_{c_n} G_n)$ is isomorphic to a coaction crossed product $C^*(\Lambda) \times_{\delta^n} G_n$. It is therefore natural to ask whether the direct limit C^*-algebra $\varinjlim(C^*(\Lambda \times_{c_n} G_n))$ is isomorphic to a coaction crossed product of $C^*(\Lambda)$ by the projective limit group $\varprojlim G_n$.

After summarising in Section 2 the background needed for our results, we answer this question in the affirmative and in greater generality in Theorem 3.1. Given a C^*-algebra A, a projective limit of finite groups G_n and a compatible system of coactions of the G_n on A, we show that there is an associated coaction δ of $\varprojlim G_n$ on A, such that $A \times_\delta (\varprojlim G_n) \cong \varinjlim(A \times_{\delta^n} G_n)$.

In Section 4, we consider the consequences of Theorem 3.1 in the original motivating context of k-graph C^*-algebras. We consider a k-graph Λ together with functors $c_n : \Lambda \to G_n$ which are consistent with the projective limit structure on the G_n. In Theorem 4.3, we use Theorem 3.1 to deduce that $C^*(\Lambda) \times_\delta G$ is isomorphic to $\varinjlim(C^*(\Lambda) \times_{\delta^n} G_n)$. Using results of [12], we realise $C^*(\Lambda) \times_\delta G$ as a full corner in a $(k+1)$-graph algebra (Corollary 4.5). We digress in Section 5 to investigate simplicity of $C^*(\Lambda) \times_\delta G$ via the results of [18].

We conclude in Section 6 with an investigation of the connection between our results and Yeend's notion of a topological k-graph [21, 20]. We construct from an infinite sequence of coverings $p_n : \Lambda_{n+1} \to \Lambda_n$ of k-graphs a projective limit Λ which is a topological k-graph. We show that the C^*-algebra $C^*(\Lambda)$ of this topological k-graph coincides with the direct limit of the $C^*(\Lambda_n)$ under the inclusions induced by the p_n. In particular, the system of cocycles $c_n : \Lambda \to G_n$ discussed in the preceding paragraph yields a cocycle $c : \Lambda \to G := \varprojlim(G_n, q_n)$, the skew-product $\Lambda \times_c G$ is a topological k-graph, and the C^*-algebras $C^*(\Lambda \times_c G)$ and $C^*(\Lambda) \times_\delta G$ are isomorphic, generalising the corresponding result [15, Theorem 7.1(ii)] for discrete groups.

2. Preliminaries

Throughout this paper, we regard $\mathbb{N}^k$ as a semigroup under addition with identity element 0. We denote the canonical generators of $\mathbb{N}^k$ by $e_1, \dots, e_k$. For $n \in \mathbb{N}^k$, we denote its coordinates by $n_1, \dots, n_k \in \mathbb{N}$ so that $n = \sum_{i=1}^k n_i e_i$. For $m, n \in \mathbb{N}^k$, we write $m \leq n$ if $m_i \leq n_i$ for all $i \in \{1, \dots, k\}$.

We will at times need to identify $\mathbb{N}^k$ with the subsemigroup of $\mathbb{N}^{k+1}$ consisting of elements n whose last coordinate is equal to zero. For $n \in \mathbb{N}^k$, we write $(n, 0)$ for the corresponding element of $\mathbb{N}^{k+1}$. When convenient, we regard $\mathbb{N}^k$ as (the morphisms of) a category with a single object in which the composition map is the usual addition operation in $\mathbb{N}^k$.

2.1. **k-graphs.** Higher-rank graphs are defined in terms of categories. In this paper, given a category $\mathcal{C}$, we will identify the objects with the identity morphisms, and think of $\mathcal{C}$ as the collection of morphisms only. We will write composition in our categories by juxtaposition.

Fix an integer $k \geq 1$. A *k-graph* is a pair (Λ, d) where Λ is a countable category and $d : \Lambda \to \mathbb{N}^k$ is a functor satisfying the factorisation property: whenever $\lambda \in \Lambda$ and $m, n \in \mathbb{N}^k$ satisfy $d(\lambda) = m + n$, there are unique $\mu, \nu \in \Lambda$ with $d(\mu) = m$, $d(\nu) = n$, and $\lambda = \mu\nu$. If $p \leq q \leq d(\lambda)$, we denote by $\lambda(p, q)$ the unique path in Λ^{q-p} such that $\lambda = \lambda'\lambda(p, q)\lambda''$ for some $\lambda' \in \Lambda^p$ and $\lambda'' \in \Lambda^{d(\lambda)-q}$

For $n \in \mathbb{N}^k$, we write Λ^n for $d^{-1}(n)$. Applying the factorisation property with $m = 0$, $n = d(\lambda)$ and with $m = d(\lambda)$, $n = 0$, one shows that Λ^0 is precisely the set of identity morphisms in Λ. The codomain and domain maps in Λ therefore determine maps $r, s : \Lambda \to \Lambda^0$. We think of Λ^0 as the vertices — and Λ as the paths — in a "k-dimensional directed graph."

Given $F \subset \Lambda$ and $v \in \Lambda^0$ we write vF for $F \cap r^{-1}(v)$ and Fv for $F \cap s^{-1}(v)$. We say that Λ is *row-finite* if $v\Lambda^n$ is a finite set for all $v \in \Lambda^0$ and $n \in \mathbb{N}^k$, and we say that Λ has *no sources* if $v\Lambda^n$ is always nonempty.

We denote by Ω_k the k-graph $\Omega_k := \{(p, q) \in \mathbb{N}^k \times \mathbb{N}^k : p \leq q\}$ with $r(p, q) := (p, p)$, $s(p, q) := (q, q)$ and $d(p, q) := q - p$. As a notational convenience, we will henceforth denote $(p, p) \in \Omega_k^0$ by p. An *infinite path* in a k-graph Λ is a degree-preserving functor (otherwise known as a *k-graph morphism*) $x : \Omega_k \to \Lambda$. The collection of all infinite paths is denoted Λ^∞. We write $r(x)$ for $x(0)$, and think of this as the range of x.

For $\lambda \in \Lambda$ and $x \in s(\lambda)\Lambda^\infty$, there is a unique infinite path $\lambda x \in r(\lambda)\Lambda^\infty$ satisfying $(\lambda x)(0, p) := \lambda x(0, p - d(\lambda))$ for all $p \geq d(\lambda)$. In particular, $r(x)x = x$ for all $x \in \Lambda^\infty$, so we denote $\{x \in \Lambda^\infty : r(x) = v\}$ by $v\Lambda^\infty$. If Λ has no sources, then $v\Lambda^\infty$ is nonempty for all $v \in \Lambda^0$.

The factorisation property also guarantees that for $x \in \Lambda^\infty$ and $n \in \mathbb{N}^k$ there is a unique infinite path $\sigma^n(x) \in x(n)\Lambda^\infty$ such that $\sigma^n(x)(p, q) = x(p + n, q + n)$. We somewhat imprecisely refer to σ as the *shift map*. Note that $\sigma^{d(\lambda)}(\lambda x) = x$ for all $\lambda \in \Lambda$, $x \in s(\lambda)\Lambda^\infty$, and $x = x(0, n)\sigma^n(x)$ for all $x \in \Lambda^\infty$ and $n \in \mathbb{N}^k$.

We say a row-finite k-graph Λ with no sources is *cofinal* if, for every $v \in \Lambda^0$ and every $x \in \Lambda^\infty$ there exists $n \in \mathbb{N}^k$ such that $v\Lambda x(n) \neq \emptyset$. Given $m \neq n \in \mathbb{N}^k$ and $v \in \Lambda^0$, we say that Λ has local periodicity m, n at v if $\sigma^m(x) = \sigma^n(x)$ for all $x \in v\Lambda^\infty$. We say that Λ has *no local periodicity* if, for every $m, n \in \mathbb{N}^k$ and every $v \in \Lambda^0$, we have $\sigma^m(x) \neq \sigma^n(x)$ for some $x \in v\Lambda^\infty$.

2.2. **Skew-products.** Let Λ be a k-graph, and let G be a group. A *cocycle* $c : \Lambda \to G$ is a functor from Λ to G where the latter is regarded as a category with one object. That is, $c : \Lambda \to G$ satisfies $c(\mu\nu) = c(\mu)c(\nu)$ whenever μ, ν can be composed in Λ. It follows that $c(v) = e$ for all $v \in \Lambda^0$, where $e \in G$ is the identity element.

Given a cocycle $c : \Lambda \to G$, we can form the *skew-product k-graph* $\Lambda \times_c G$. We follow the conventions of [15, Section 6]. Note that these are different to those of [9, Section 5]. The paths in $\Lambda \times_c G$ are

$$(\Lambda \times_c G)^n := \Lambda^n \times G$$

for each $n \in \mathbb{N}^k$. The range and source maps $r, s : \Lambda \times_c G \to (\Lambda \times_c G)^0$ are given by $r(\lambda, g) := (r(\lambda), c(\lambda)g)$ and $s(\lambda, g) := (s(\lambda), g)$. Composition is determined by $(\mu, c(\nu)g)(\nu, g) = (\mu\nu, g)$. It is shown in [15, Section 6] that $\Lambda \times_c G$ is a k-graph.

2.3. **Coverings and $(k+1)$-graphs.** We recall here some definitions and results from [12] regarding coverings of k-graphs. Given k-graphs Λ and Γ, a k-graph morphism $\phi : \Lambda \to \Gamma$ is a functor which respects the degree maps. A *covering of k-graphs* is a triple (Λ, Γ, p) where Λ and Γ are k-graphs, and $p : \Gamma \to \Lambda$ is a k-graph morphism which is surjective and is locally bijective in the sense that for each $v \in \Gamma^0$, the restrictions $p|_{v\Gamma} : v\Gamma \to p(v)\Lambda$ and $p|_{\Gamma v} : \Gamma v \to \Lambda p(v)$ are bijective.

Remark 2.1. What we have called a covering of k-graphs is a special case of what was called a "covering system of k-graphs" in [12]. In general, a covering system consists of a covering of k-graphs together with some extra combinatorial data. We do not need the extra generality, so we have dropped the word "system."

A covering (Λ, Γ, p) is *row-finite* if Λ (equivalently Γ) is row-finite, and $|p^{-1}(v)| < \infty$ for all $v \in \Lambda^0$. Proposition 2.6 of [12] shows that we can associate to a row-finite covering $p : \Gamma \to \Lambda$ of k-graphs a row-finite $(k+1)$-graph $\Lambda \overset{p}{\leftarrow} \Gamma$ containing disjoint copies $\imath(\Lambda)$ and $\jmath(\Gamma)$ of Λ and Γ with an edge of degree e_{k+1} connecting each vertex $\jmath(v) \in \jmath(\Gamma^0)$ to its image $\imath(p(v)) \in \imath(\Lambda^0)$.

More generally, given a sequence $(\Lambda_n, \Lambda_{n+1}, p_n)$ of row-finite coverings of k-graphs, Corollary 2.10 of [12] shows how to build a $(k+1)$-graph $\varprojlim(\Lambda_n; p_n)$, which we sometimes refer to as a *tower graph*, containing a copy $\imath_n(\Lambda_n)$ of each individual k-graph in the sequence, and an edge of degree e_{k+1} connecting each $\imath_{n+1}(v) \in \imath_{n+1}(\Lambda^0_{n+1})$ to its image $\imath_n(p_n(v)) \in \imath_n(\Lambda^0_n)$. The $(k+1)$-graph $\varprojlim(\Lambda_n; p_n)$ has no sources if the Λ_n all have no sources.

Given a covering (Λ, Γ, p), [12, Proposition 3.2 and Theorem 3.8] show that the covering map $p : \Gamma \to \Lambda$ induces an inclusion $\iota_p : C^*(\Lambda) \to C^*(\Gamma)$. If $(\Lambda_n, \Lambda_{n+1}, p_n)_{n=1}^{\infty}$ is a sequence of coverings, the $(k+1)$-graph algebra $C^*(\varprojlim(\Lambda_n; p_n))$ is Morita equivalent to the direct limit $\varinjlim(C^*(\Lambda_n), \iota_{p_n})$.

2.4. **Coactions and coaction crossed products.** Here we give some background on group coactions on C^*-algebras and coaction crossed products. For a detailed treatment of coactions and coaction crossed-products, see [4, Appendix A].

Given a locally compact group G, we write $C^*(G)$ for the full group C^*-algebra of G. We prefer to identify G with its canonical image in $M(C^*(G))$, but when confusion is likely we use $s \mapsto u(s)$ for the canonical inclusion of G in $M(C^*(G))$. If A and B are C^*-algebras, then $A \otimes B$ denotes the spatial tensor product. For a group G, we write δ_G for the natural comultiplication $\delta_G : C^*(G) \to M(C^*(G) \otimes C^*(G))$ given by the integrated form of the strictly continuous map which takes $s \in G$ to $s \otimes s \in \mathcal{U}M(C^*(G) \otimes C^*(G))$.

As in [4, Definition A.21], a *coaction* of a group G on a C^*-algebra A is an injective homomorphism $\delta : A \to M(A \otimes C^*(G))$ satisfying

(1) the *coaction identity* $(\delta \otimes 1_G) \circ \delta = (1_A \otimes \delta_G) \circ \delta$ (as maps from A to $M(A \otimes C^*(G) \otimes C^*(G))$); and
(2) the *nondegeneracy condition* $\overline{\delta(A)(1_A \otimes C^*(G))} = M(A \otimes C^*(G))$.

As in [7, 8], the nondegeneracy condition (2) — rather than the weaker condition that δ be a nondegenerate homomorphism — is part of our definition of a coaction (cf. Definition A.21 and Remark A.22(3) of [4]). Since we will be dealing only with coactions of compact (and hence amenable) groups, the two conditions are equivalent in our setting in any case (see [14, Lemma 3.8]).

Let $\delta : A \to M(A \otimes C^*(G))$ be a coaction of G on A. We regard the map which takes $s \in G$ to $u(s) \in M(C^*(C))$ as an element w_G of $\mathcal{U}M(C_0(G) \otimes C^*(G))$. Given a C^*-algebra D, A *covariant homomorphism* of (A, G, δ) into $M(D)$ is a pair (π, μ) of homomorphisms $\pi : A \to M(D)$ and $\mu : C_0(G) \to M(D)$ satisfying the covariance condition:

$$(\pi \otimes \mathrm{id}_G) \circ \delta(a) = (\mu \otimes \mathrm{id}_G)(w_G)(\pi(a) \otimes 1)(\mu \otimes \mathrm{id}_G)(w_G)^*$$

for all $a \in A$.

The coaction crossed-product $A \rtimes_\delta G$ is the universal C^*-algebra generated by the image of a universal covariant representation (j_A, j_G) of (A, G, δ) (see [4, Theorem A.41]).

3. Continuity of coaction crossed-products

In this section, we prove a general result regarding the continuity of the coaction crossed-product construction. Specifically, consider a projective system of finite groups G_n and a system of compatible coactions δ^n of the G_n on a fixed C^*-algebra A. We show that this determines a coaction δ of the projective limit $\varprojlim G_n$ on A, and that the coaction crossed product of A by δ is isomorphic to a direct limit of the coaction crossed products of A by the δ^n.

The application we have in mind is when $A = C^*(\Lambda)$ is a k-graph algebra, and the δ^n arise from a system of skew-products of Λ by the G_n. We consider this situation in Section 4.

Theorem 3.1. *Let A be a C^*-algebra, and let*

$$\cdots \xrightarrow{q_{n+1}} G_{n+1} \xrightarrow{q_n} G_n \longrightarrow \cdots \xrightarrow{q_1} G_1$$

be surjective homomorphisms of finite groups. For each n let δ^n be a coaction of G_n on A. Suppose that the diagram

(1)
$$\begin{array}{ccc} A & \xrightarrow{\delta^{n+1}} & M(A \otimes C^*(G_{n+1})) \\ & \searrow^{\delta^n} & \downarrow{\scriptstyle \mathrm{id}\otimes q_n} \\ & & M(A \otimes C^*(G_n)) \end{array}$$

commutes for each n.

For each n, write Q_n for the canonical surjective homomorphism of $\varprojlim(G_m, q_m)$ onto G_n; write $q_n^* : C(G_n) \to C(G_{n+1})$ for the induced map $q_n^*(f) := f \circ q_n$; and write J_n for the homomorphism $J_n := j_A^{\delta^{n+1}} \times (j_{G_{n+1}} \circ q_n^*)$ from $A \times_{\delta^n} G_n$ to $A \times_{\delta^{n+1}} G_{n+1}$.

Then there is a unique coaction δ of $\varprojlim(G_n, q_n)$ on A such that:

(i) *the diagrams*

$$\begin{array}{ccc} A & \xrightarrow{\delta} & M(A \otimes C^*(\varprojlim G_n)) \\ & \searrow^{\delta^n} & \downarrow{\scriptstyle \mathrm{id}\otimes Q_n} \\ & & M(A \otimes C^*(G_n)) \end{array}$$

commute; and

(ii) $A \times_\delta \varprojlim(G_n, q_n) \cong \varinjlim(A \times_{\delta^n} G_n, J_n)$.

Remark 3.2. In equation (1) we could replace $M(A \otimes C^*(G_n))$ with $A \otimes C^*(G_n)$ and $M(A \otimes C^*(G_{n+1}))$ with $A \otimes C^*(G_{n+1})$ because G_n, G_{n+1} are discrete.

Proof of Theorem 3.1. Put

$$\begin{aligned} G &= \varprojlim G_n \\ B_n &= A \times_{\delta^n} G_n \\ J_n &= j_A^{\delta^{n+1}} \times (j_{G_{n+1}} \circ q_n^*) : B_n \to B_{n+1} \\ B &= \varinjlim(B_n, J_n) \\ K_n &= \text{ the canonical embedding } B_n \to B. \end{aligned}$$

We aim to apply Landstad duality [17]: we will show that B is of the form $C \times_\delta G$ for some coaction (C, G, δ), and then we will show that we can take $C = A$. To apply [17] we need:

- an action α of G on B, and
- a nondegenerate homomorphism $\mu : C(G) \to M(B)$ which is $\mathrm{rt} - \alpha$ equivariant, where rt is the action of G on $C(G)$ by right translation.

Then [17] will provide a coaction (C, G, δ) and an isomorphism

$$\theta : B \xrightarrow{\cong} C \times_\delta G$$

such that

$$\theta \circ \mu = j_G \quad \text{and} \quad \theta(B^\alpha) = j_C(C).$$

This is simpler than the general construction of [17], because our group G is compact (and then we are really using Landstad's unpublished characterisation [13] of crossed products by coactions of compact groups).

We begin by constructing the action α: for each $s \in G$ the diagrams

$$\begin{array}{ccc} B_{n+1} & \xrightarrow{\widehat{\delta^{n+1}}_{Q_{n+1}(s)}} & B_{n+1} \\ {\scriptstyle J_n}\uparrow & & \uparrow{\scriptstyle J_n} \\ B_n & \xrightarrow[\widehat{\delta^n}_{Q_n(s)}]{} & B_n \end{array}$$

commute because

$$\begin{aligned}\widehat{\delta^{n+1}}_{Q_{n+1}(s)} \circ J_n \circ j_A^{\delta^n} &= \widehat{\delta^{n+1}}_{Q_{n+1}(s)} \circ j_A^{\delta^{n+1}} \\ &= j_A^{\delta^{n+1}} \\ &= J_n \circ j_A^{\delta^n} \\ &= J_n \circ \widehat{\delta^n}_{Q_n(s)} \circ j_A^{\delta^n}\end{aligned}$$

and

$$\begin{aligned}\widehat{\delta^{n+1}}_{Q_{n+1}(s)} \circ J_n \circ j_{G_n} &= \widehat{\delta^{n+1}}_{Q_{n+1}(s)} \circ j_{G_{n+1}} \circ q_n^* \\ &= j_{G_{n+1}} \circ \mathrm{rt}_{Q_{n+1}(s)} \circ q_n^* \\ &= j_{G_{n+1}} \circ q_n^* \circ \mathrm{rt}_{q_n \circ Q_{n+1}(s)} \\ &= J_n \circ j_{G_n} \circ \mathrm{rt}_{Q_n(s)} \\ &= J_n \circ \widehat{\delta^n}_{Q_n(s)} \circ j_{G_n}.\end{aligned}$$

Thus, because the $\widehat{\delta^n}_{Q_n(s)}$ are automorphisms, by universality there is a unique automorphism α_s such that the diagrams

$$\begin{array}{ccc} B & \overset{\alpha_s}{\dashrightarrow} & B \\ {\scriptstyle K_n}\uparrow & & \uparrow{\scriptstyle K_n} \\ B_n & \underset{\widehat{\delta^n}_{Q_n(s)}}{\longrightarrow} & B_n \end{array}$$

commute. It is easy to check that this gives a homomorphism $\alpha : G \to \operatorname{Aut} B$. We verify continuity: each function $s \mapsto \alpha_s(b)$ for $b \in B$ is a uniform limit of functions of the form $s \mapsto \alpha_s \circ K_n(b)$ for $b \in B_n$. But we have

$$\alpha_s \circ K_n(b) = K_n \circ \widehat{\delta^n}_{Q_n(s)}(b),$$

which is continuous since K_n, Q_n, and $t \mapsto \widehat{\delta^n}_t(b) : G_n \to B_n$ are.

We turn to the construction of the nondegenerate homomorphism μ: first note that the increasing union $\bigcup_n Q_n^*(C(G_n))$ is dense in $C(G)$ by the Stone-Weierstrass Theorem, and it follows that there is an isomorphism

$$C(G) \cong \varinjlim (C(G_n), q_n^*)$$

taking Q_n to the canonical embedding. We have a compatible sequence of nondegenerate homomorphisms

$$\begin{array}{ccc} C(G_{n+1}) & \overset{j_{G_{n+1}}}{\longrightarrow} & M(B_{n+1}) \\ {\scriptstyle q_n^*}\uparrow & & \uparrow{\scriptstyle J_n} \\ C(G_n) & \underset{j_{G_n}}{\longrightarrow} & M(B_n), \end{array}$$

so by universality there is a unique homomorphism μ making the diagrams

$$\begin{CD} C(G) @>{\mu}>> M(B) \\ @A{Q_n^*}AA @AA{K_n}A \\ C(G_n) @>>{j_{G_n}}> M(B_n) \end{CD}$$

commute. Moreover, μ is nondegenerate since K_n and j_{G_n} are.

We now have α and μ, and the equivariance

$$\alpha_s \circ \mu = \mu \circ \mathrm{rt}_s$$

follows from

$$\begin{aligned} \alpha_s \circ \mu \circ Q_n^* &= \alpha_s \circ K_n \circ j_{G_n} \\ &= K_n \circ \widehat{\delta^n}_{Q_n(s)} \circ j_{G_n} \\ &= K_n \circ j_{G_n} \circ \mathrm{rt}_{Q_n(s)} \\ &= \mu \circ Q_n^* \circ \mathrm{rt}_{Q_n(s)} \\ &= \mu \circ \mathrm{rt}_s \circ Q_n^*. \end{aligned}$$

Thus we can apply [17] to obtain a coaction (C, G, δ) and an isomorphism

$$\theta : B \xrightarrow{\cong} C \times_\delta G$$

such that

$$\theta \circ \mu = j_G \quad \text{and} \quad \theta(B^\alpha) = j_C(C).$$

We want to take $C = A$. Note that we have a compatible sequence of nondegenerate homomorphisms

$$\begin{array}{ccc} A & \xrightarrow{j_A^{\delta^{n+1}}} & B_{n+1} \\ & {\scriptstyle j_A^{\delta^n}} \searrow & \uparrow {\scriptstyle J_n} \\ & & B_n, \end{array}$$

so by universality there is a unique homomorphism j making the diagrams

$$\begin{array}{ccc} A & \xrightarrow{j} & B \\ & {\scriptstyle j_A^{\delta^n}} \searrow & \uparrow {\scriptstyle K_n} \\ & & B_n \end{array}$$

commute. Moreover, j is injective and nondegenerate since K_n and $j_A^{\delta^n}$ are. Because j, j_C, and θ are faithful, to show that we can take $C = A$ it suffices to show that

$$j(A) = B^\alpha.$$

We have

$$j(A) \subset B^\alpha$$

because

$$\begin{aligned}\alpha_s \circ j &= \alpha_s \circ K_n \circ j_A^{\delta_n}\\ &= K_n \circ \widehat{\delta^n}_{Q_n(s)} \circ j_A^{\delta_n}\\ &= K_n \circ j_A^{\delta_n}\\ &= j.\end{aligned}$$

For the opposite containment, let $b \in B^\alpha$. There is a sequence $b_n \in B_n$ such that $K_n(b_n) \to b$. The functions $s \mapsto \alpha_s \circ K_n(b)$ converge uniformly to the function $s \mapsto \alpha_s(b)$, so

$$\int_G \alpha_s \circ K_n(b_n)\, ds \to \int_G \alpha_s(b)\, ds = b.$$

We have

$$\int_G \alpha_s \circ K_n(b_n)\, ds = \int_G K_n \circ \widehat{\delta^n}_{Q_n(s)}(b_n)\, ds = K_n \left(\int_G \widehat{\delta^n}_{Q_n(s)}(b_n)\, ds\right).$$

Since

$$\int_G \widehat{\delta^n}_{Q_n(s)}(b_n)\, ds \in B_n^{\widehat{\delta^n}} = j_A^{\delta^n}(A),$$

we conclude that

$$b \in K_n \circ j_A^{\delta^n}(A) = j(A).$$

Therefore we can take $C = A$, so that we have a coaction (A, G, δ) and an isomorphism

$$\theta : B \xrightarrow{\cong} A \times_\delta G$$

such that

$$\theta \circ \mu = j_G.$$

We have proved (ii). For (i), we calculate:

$$\begin{aligned}(j_A^\delta \otimes \delta) \circ (\mathrm{id} \otimes q_n) \circ \delta &= (\mathrm{id} \otimes q_n) \circ (j_A^\delta \otimes \mathrm{id}) \circ \delta\\ &= (\mathrm{id} \otimes q_n) \circ \mathrm{Ad}(j_G \otimes \mathrm{id})(w_G) \circ (j_A^\delta \otimes 1)\\ &= \mathrm{Ad}(\mathrm{id} \otimes q_n)\big((j_G \otimes \mathrm{id})(w_G)\big) \circ (\mathrm{id} \otimes q_n) \circ (j_A^\delta \otimes 1)\\ &= \mathrm{Ad}(j_G \otimes \mathrm{id})\big((\mathrm{id} \otimes q_n)(w_G)\big) \circ (j_A^\delta \otimes 1)\\ &= \mathrm{Ad}(j_G \otimes \mathrm{id})\big((Q_n^* \otimes \mathrm{id})(w_{G_n})\big) \circ (j_A^\delta \otimes 1)\\ &= \mathrm{Ad}(j_G \circ Q_n^* \otimes \mathrm{id})(w_{G_n}) \circ (j_A^\delta \otimes 1)\\ &= \mathrm{Ad}(K_n \circ j_{G_n} \otimes \mathrm{id})(w_{G_n}) \circ (K_n \circ j_A^{\delta^n} \otimes 1)\\ &= (K_n \otimes \mathrm{id}) \circ \mathrm{Ad}(j_{G_n} \otimes \mathrm{id})(w_{G_n}) \circ (j_A^{\delta^n} \otimes 1)\\ &= (K_n \otimes \mathrm{id}) \circ (j_A^{\delta^n} \otimes \mathrm{id}) \circ \delta^n\\ &= (K_n \circ j_A^{\delta^n} \otimes \mathrm{id}) \circ \delta^n\\ &= (j_A^\delta \otimes \mathrm{id}) \circ \delta^n.\end{aligned}$$

Since j_A^δ is faithful, we therefore have $\delta \circ (\mathrm{id} \otimes q_n) = \delta^n$. □

The following application of Theorem 3.1 motivates the work of the following sections.

Example 3.3. Let $A = C(\mathbb{T}) = C^*(\mathbb{Z})$, and let z denote the canonical generating unitary function $z \mapsto z$. For $n \in \mathbb{N}$, let $G_n := \mathbb{Z}/2^{n-1}\mathbb{Z}$ be the cyclic group of order 2^{n-1}. We write 1 for the canonical generator of G_n and 0 for the identity element. Let $g \mapsto u_n(g)$ denote the canonical embedding of G_n into $C^*(G_n)$. Define $q_n : G_{n+1} \to G_n$ by $q_n(m) := m \pmod{2^{n-1}}$, and write q_n also for the homomorphism $q_n : C^*(G_{n+1}) \to C^*(G_n)$ satisfying $q_n(u_{n+1}(g)) = u_n(q_n(g))$. For each n, let δ^n be the coaction of G_n on A determined by $\delta^n(z) := z \otimes u_n(1)$.

Let $g \mapsto u(g)$ denote the canonical embedding of $\varprojlim G_n$ as unitaries in the multiplier algebra of $C^*(\varprojlim G_n)$. The coaction δ of $\varprojlim G_n$ on A described in Theorem 3.1 is the one determined by $\delta(z) := z \otimes u(1, 1, \dots)$; the corresponding coaction crossed-product is known to be isomorphic to the Bunce-Deddens algebra of type 2^∞ (see, for example, [6, 8.4.4]).

4. Coverings of skew-products

In this section and the next, we adopt the following notation and assumptions.

Notation 4.1. Let Λ be a connected row-finite k-graph with no sources. Fix a vertex $v \in \Lambda^0$, and denote by $\pi\Lambda$ the fundamental group $\pi_1(\Lambda, v)$ of Λ with respect to v. Fix a cocycle $c : \Lambda \to \pi\Lambda$ such that the skew product $\Lambda \times_c \pi\Lambda$ is isomorphic to the universal covering Ω_Λ of Λ (such a cocycle exists by [15, Corollary 6.5]).

Fix a descending chain of finite-index normal subgroups

$$\cdots \lhd H_{n+1} \lhd H_n \lhd \cdots \lhd H_1 := \pi\Lambda. \tag{2}$$

For each n, let $G_n := \pi\Lambda/H_n$, and let $q_n : G_{n+1} \to G_n$ be the induced homomorphism

$$q_n(gH_{n+1}) := gH_n.$$

Then

$$\cdots \xrightarrow{q_{n+1}} G_{n+1} \xrightarrow{q_n} G_n \longrightarrow \cdots \xrightarrow{q_1} G_1 := \{e\}$$

is a chain of surjective homomorphisms of finite groups. Let G denote the projective limit group $\varprojlim(G_n, q_n)$.

For each n, let $c_n : \Lambda \to G_n$ be the induced cocycle $c_n(\lambda) = c(\lambda)H_n$, and let

$$\Lambda_n := \Lambda \times_{c_n} G_n$$

be the skew-product k-graph. Define covering maps $p_n : \Lambda_{n+1} \to \Lambda_n$ by $p_n(\lambda, g) := (\lambda, q_n(g))$.

As in [15, Theorem 7.1(1)], for each n there is a coaction $\delta^n : C^*(\Lambda) \to C^*(\Lambda) \otimes C^*(G_n)$ determined by $\delta^n(s_\lambda) := s_\lambda \otimes c_n(\lambda)$. Denote by J_n the inclusion

$$J_n := j_A^{\delta^{n+1}} \times (j_{G_{n+1}} \circ q_n^*) : C^*(\Lambda) \times_{\delta^n} G_n \to C^*(\Lambda) \times_{\delta^{n+1}} G_{n+1}$$

described in Theorem 3.1(ii).

As in [15, Theorem 7.1(ii)], for each n there is an isomorphism ϕ_n of $C^*(\Lambda_n) = C^*(\Lambda \times_{c_n} G_n)$ onto $C^*(\Lambda) \times_{\delta^n} (G_n)$ which satisfies $\phi_n(s_{(\lambda,g)}) := (s_\lambda, g)$.

Example 4.2 (Example 3.3 Continued). Let Λ be the path category of the directed graph B_1 consisting of a single vertex v and a single edge f with $r(f) = s(f) = v$. Note that as a category, Λ is isomorphic to $\mathbb{N}$, and the degree functor is then the identity function from $\mathbb{N}$ to itself.

Then $\pi\Lambda$ is the free abelian group generated by the homotopy class of f, and so is isomorphic to $\mathbb{Z}$. We define a functor $c : \Lambda \to \mathbb{Z}$ by $c(f) = 1$.

For each n, let $H_n := 2^{n-1}\mathbb{Z} \subset \mathbb{Z}$, so that $\cdots \lhd H_{n+1} \lhd H_n \lhd \cdots \lhd H_1 := \pi\Lambda$ is a descending chain of finite-index normal subgroups. For each n, $G_n := \mathbb{Z}/H_n$ is the cyclic group of order 2^{n-1}, and $q_n : G_{n+1} \to G_n$ is the quotient map described in Example 3.3. The induced cocycle $c_n : \Lambda \to G_n$ obtained from c is determined by $c_n(f) = 1 \in \mathbb{Z}/2^{n-1}\mathbb{Z}$.

For $p \in \mathbb{N}$, let C_p denote the simple cycle graph with p vertices: $C_p^0 := \{v_j^p : j \in \mathbb{Z}/p\mathbb{Z}\}$ and $C_p^1 := \{e_j^p : j \in \mathbb{Z}/p\mathbb{Z}\}$, where $r(e_i^p) = v_i^p$ and $s(e_i^p) = v_{i+1 \bmod p}^p$. For each n, the skew-product graph $\Lambda_n := \Lambda \times_{c_n} G_n$ is isomorphic to the path-category of $C_{2^{n-1}}$. The associated covering map $p_n : \Lambda_{n+1} \to \Lambda_n$ corresponds to the double-covering of $C_{2^{n-1}}$ by C_{2^n} satisfying $v_i^{2^n} \mapsto v_{i \bmod 2^{n-1}}^{2^{n-1}}$ and $e_i^{2^n} \mapsto e_{i \bmod 2^{n-1}}^{2^{n-1}}$.

Modulo a relabelling of the generators of $\mathbb{N}^2$, the 2-graph $\varprojlim(\Lambda_n, p_n)$ obtained from this data as in [12] (see Section 2.3) is isomorphic to the 2-graph of [16, Example 6.7]. Combining this with the final observation of Example 3.3, we obtain a new proof that the C^*-algebra of this 2-graph is Morita equivalent to the Bunce-Deddens algebra of type 2^∞.

Theorem 4.3. *Adopt the notation and assumptions* 4.1*. Taking $A := C^*(\Lambda)$, the coactions δ^n and the quotient maps q_n make the diagrams* (1) *commute. Let δ denote the coaction of $G := \varprojlim(G_n, q_n)$ on $C^*(\Lambda)$ obtained from Theorem* 3.1*. Let P_0 denote the projection $\sum_{v\in\Lambda^0} s_v$ in the multiplier algebra of $C^*(\varprojlim(\Lambda_n, p_n))$. Then P_0 is full and*

$$P_0 C^*(C^*(\varprojlim(\Lambda_n, p_n)))P_0 \cong C^*(\Lambda) \times_\delta G.$$

To prove this theorem, we first show that in the setting described above, the inclusions of k-graph algebras induced from the coverings $p_n : \Lambda_{n+1} \to \Lambda_n$ as in [12] are compatible with the inclusions of coaction crossed products induced from the quotient maps $q_n : G_{n+1} \to G_n$.

Lemma 4.4. *With the notation and assumptions* 4.1*, fix $n \in \mathbb{N}$, and let ι_{p_n} be the inclusion of $C^*(\Lambda_n)$ into $C^*(\Lambda_{n+1})$ obtained from* [12, Proposition 3.3(iv)]*. Then the inclusion ι_n and the isomorphisms ϕ_n, ϕ_{n+1} of Notation* 4.1 *make the following diagram commute.*

$$\begin{array}{ccc} C^*(\Lambda_n) & \xrightarrow{\iota_{p_n}} & C^*(\Lambda_{n+1}) \\ \downarrow \phi_n & & \downarrow \phi_{n+1} \\ C^*(\Lambda) \times_{\delta^n} G_n & \xrightarrow{\iota_n} & C^*(\Lambda) \times_{\delta^{n+1}} G_{n+1} \end{array}$$

Proof. By definition, we have

$$\iota_{p_n}(s_{(\lambda, gH_n)}) = \sum_{p(\lambda', g'H_{n+1}) = (\lambda, gH_n)} s_{(\lambda', g'H_{n+1})}.$$

By definition of p_n, this becomes

$$\iota_p(s_{(\lambda,gH_n)}) = \sum_{\{g'H_{n+1}\in G_{n+1}: g'H_n = gH_n\}} s_{(\lambda,g'H_{n+1})}.$$

Hence

$$\phi_{n+1}\circ\iota_{p_n}(s_{(\lambda,gH_n)}) = \sum_{\{g'H_{n+1}\in G_{n+1}: g'H_n = gH_n\}} (s_\lambda, g'H_{n+1}).$$

But this is precisely $\iota(\phi_n(s_{(\lambda,gH_n)}))$ by definition of ι and ϕ_n. □

Corollary 4.5. *With the notation and assumptions* 4.1*, let P_0 denote the projection $\sum_{v\in\Lambda^0} s_v$ in the multiplier algebra of $C^*(\varprojlim(\Lambda_n,p_n))$. Then P_0 is full, and*

$$P_0 C^*(\varprojlim(\Lambda_n,p_n))P_0 \cong \varinjlim(C^*(\Lambda)\times_{\delta^n} G_n, \iota_n).$$

Proof. Equation (3.2) of [12] implies that $P_0C^*(\varprojlim(\Lambda_n,p_n))P_0$ is isomorphic to $\varinjlim(C^*(\Lambda_n),\iota_{p_n})$. The latter is isomorphic to $\varinjlim(C^*(\Lambda)\times_{\delta^n} G_n,\iota_n)$ by Lemma 4.4 and the universal property of the direct limit. □

Proof of Theorem 4.3. It is immediate from the definitions of the maps involved that the maps δ^n and q_n make the diagram (1) commute. The rest of the statement then follows from Corollary 4.5 and Theorem 3.1(ii). □

5. Simplicity

In this section we frequently embed $\mathbb{N}^k$ into $\mathbb{N}^{k+1}$ as the subset consisting of elements whose $(k+1)^{\text{st}}$ coordinate is equal to zero. For $n\in\mathbb{N}^k$, we write $(n,0)$ for the corresponding element of $\mathbb{N}^{k+1}$.

Theorem 5.1. *Adopt the notation and assumptions* 4.1*. Then $C^*(\varprojlim(\Lambda_n,p_n))$ is simple if and only if the following two conditions are satisfied:*

(i) *each Λ_n is cofinal, and*
(ii) *whenever $v\in\Lambda^0$, $p\neq q\in\mathbb{N}^k$ satisfy $\sigma^p(x)=\sigma^q(x)$ for all $x\in v\Lambda^0$, there exists $x\in v\Lambda^\infty$, $l\in\mathbb{N}^k$ and $N\in\mathbb{N}$ such that $c_N(x(p,p+l))\neq c_N(x(q,q+l))$.*

The idea is to prove the theorem by appealing to [18, Theorem 3.1]. To do this, we will first describe the infinite paths in $\varprojlim(\Lambda_n,p_n)$. We identify $\varprojlim(G_n,q_n)$ with the set of sequences $g=(g_n)_{n=1}^\infty$ such that $q_n(g_{n+1})=g_n$ for all n.

Lemma 5.2. *Adopt the notation and assumptions* 4.1*. Fix $x\in\Lambda^\infty$ and $g=(g_n)_{n=1}^\infty\in\varprojlim(G_n,q_n)$. For each $n\in\mathbb{N}$ there is a unique infinite path $(x,g_n)\in\Lambda_n^\infty$ determined by $(x,g_n)(0,m)=(x(0,m),c_n(x(0,m))^{-1}g_n)$ for all $m\in\mathbb{N}^k$. There is a unique infinite path $x^g\in(\varprojlim(\Lambda_n,p_n))$ such that $x^g(0,(m,0))=x(0,m)$ for all $m\in\mathbb{N}^k$ and $x^g(ne_{k+1})=(x(0),g_n)$ for all $n\in\mathbb{N}$; moreover $\sigma^{ne_{k+1}}(x^g)(0,(m,0))=(x,g_n)(0,m)$ for all $m\in\mathbb{N}^k$. Finally, every infinite path $y\in(\varprojlim(\Lambda_n,p_n))^\infty$ is of the form $\sigma^{ne_{k+1}}(x^g)$ for some $n\in\mathbb{N}$, $x\in\Lambda^\infty$ and $g\in\varprojlim(G_n,q_n)$.*

Proof. That the formula given determines unique infinite paths (x,g_n), $n\in\mathbb{N}$ follows from [9, Remarks 2.2]. That there is a unique infinite path x^g such that

$x^g(0,(m,0)) = x(0,m)$ for all $m \in \mathbb{N}^k$ and $x^g(ne_{k+1}) = (x(0), g_n)$ for all $n \in \mathbb{N}$ follows from the observation that for each $n \in \mathbb{N}$ there is a unique path

$$\alpha = \alpha_{g,n} := e(x(0), g_1)e(x(0), g_2)\cdots e(x(0), g_n)$$

with $d(\alpha_{g,n}) = ne_{k+1}$, $r(\alpha) = x(0) \in \Lambda^0$ and $s(\alpha) = (x(0), g_n) \in \Lambda^0_n$, and that for each $m \in \mathbb{N}^k$,

$$\alpha(x, g_n)(0, m) = x(0, m)e(x(m), c_1(x(0, m))^{-1}g_1)\cdots e(x(m), c_n(x(0, m))^{-1}g_n)$$

is the unique minimal common extension of $x(0,m)$ and α. This also establishes the assertion that $\sigma^{ne_{k+1}}(x^g)(0,(m,0)) = (x, g_n)(0,m)$ for all $m \in \mathbb{N}^k$.

For the final assertion, fix $y \in (\varprojlim(\Lambda_n, p_n))^\infty$. We must have $y(0) = (v, g_n)$ for some $v \in \Lambda^0$, $g_n \in G_n = \pi\Lambda/H_n$ and $n \in \mathbb{N}$. Let $x \in \Lambda^\infty_n$ be the infinite path determined by $x(0,m) := y(0,(m,0))$ for all $m \in \mathbb{N}^k$. By definition of $\Lambda_n = \Lambda \times_{c_n} G_n$, we have $x(0,m) := (\alpha_m, c_n(\alpha_m)^{-1}g_n)$ where each $\alpha_m \in v\Lambda^m$ and g is the element of $\pi\Lambda$ such that $y(0) = v(g_n)$ as above. There is then an infinite path in $x' \in \Lambda^\infty$ determined by $x'(0,m) = \alpha_m$ for all $m \in \mathbb{N}^k$. For $n > i \geq 1$, inductively define $g_i := q_i(g_{i+1})$, and for $n < i$ let g_i be the unique element of G_i such that $y((i-n)e_{k+1}) = (v, g_i)$; that such g_i exist follows from the definition of $\varprojlim(\Lambda_n, p_n)$. Then $g := (g_i)_{i=1}^\infty$ is an element of $\varprojlim(G_n, q_n)$ by definition, and routine calculations using the definitions of the Λ_n show that $x = \sigma^{ne_{k+1}}((x')^g)$. □

Lemma 5.3. *Adopt the notation and assumptions* 4.1. *Then the* $(k+1)$*-graph* $\varprojlim(\Lambda_n, p_n)$ *is cofinal if and only if each* Λ_n *is cofinal.*

Proof. First suppose that each Λ_n is cofinal. Fix $y \in \varprojlim(\Lambda_n, p_n)$ and $w \in \varprojlim(\Lambda^0)$. By Lemma 5.2, we have $y = \sigma^{i_0 e_{k+1}}(x^g)$ for some $g = (g_n)_{n=1}^\infty \in \varprojlim(G_n, q_n)$, some $i_0 \in \mathbb{N}$ and some $x \in \Lambda^\infty$. We must show that $w(\varprojlim(\Lambda_n, p_n))y(q) \neq \emptyset$ for some q. We have $w \in \Lambda^0_m$ for some $m \in \mathbb{N}$, so $w = (w', h)$ for some $h \in G_m$. If $m < i_0$, fix any $h' \in \pi\Lambda$ such that $h'H_{i_0} = h$, and note that $w(\varprojlim(\Lambda_n, p_n))(w', hH_{i_0})$ is nonempty, so that it suffices to show that $(w', h'H_{i_0})\varprojlim(\Lambda_n, p_n))y(q) \neq \emptyset$ for some q. That is to say, we may assume without loss of generality that $m \geq i_0$. But now $w \in \Lambda^0_m$ and $\sigma^{(0,\dots,0,m-i_0)}(y) \in (\varprojlim(\Lambda_n, p_n))^\infty$ with $r(y) \in \Lambda^0_{i_0}$. Since Λ_n is cofinal, we have $w\Lambda_{i_0}(x, g_m)(q) \neq \emptyset$ for some $q \in \mathbb{N}^k$ (recall that $x, (g_i)_{i=1}^\infty$ are such that $y = \sigma^{i_0 e_{k+1}}(x^g)$). By definition, $(x, g_m)(q) = y(q_1, \dots, q_k, m - i_0)$ and this shows that $w(\varprojlim(\Lambda_n, p_n))y(q) \neq \emptyset$ for $q = (q_1, \dots, q_k, m - n)$.

Now suppose that $\varprojlim(\Lambda_n, p_n)$ is cofinal. Fix $n \in \mathbb{N}$ and a vertex w and an infinite path x in Λ_n. Then $x(0) = (v, gH_n)$ for some $v \in \Lambda^0$, $g \in \pi\Lambda$. There are paths $\alpha_m \in \Lambda^m_n$, $m \in \mathbb{N}^k$ determined by $x(0,m) = (\alpha_m, c_n(\alpha_m)^{-1}gH_n)$; there is then an infinite path $x' \in \Lambda^\infty$ such that $x'(0,m) = \alpha_m$ for all m. Let $g_i := gH_i$ for all $i \in \mathbb{N}$. By abuse of notation we denote by g the element $(gH_i)_{i=1}^\infty$ of $\varprojlim(G_n, q_n)$. Let $y = \sigma^n((x')^g)$ be the infinite path of $(\varprojlim(\Lambda_n, p_n)$ provided by Lemma 5.2. As $\varprojlim(\Lambda_n, p_n)$ is cofinal, we may fix a path $\lambda \in \varprojlim(\Lambda_n, p_n)$ such that $r(\lambda) = w$ and $s(\lambda)$ lies on y. By definition of y, there exist $n' \geq n$ and $m \in \mathbb{N}^k$ such that $s(\lambda) = (x'(m), c_{n'}(\alpha_m)^{-1}g_{n'})$. We then have $d(\lambda)_{k+1} = n' - n$, and we may factorise $\lambda = \lambda'\lambda''$ where $d(\lambda') = d(\lambda) - (n'-n)e_{k+1}$ and $d(\lambda'') = (n'-n)e_{k+1}$. By construction of $\varprojlim(\Lambda_n, p_n)$, if $d(\mu) = je_{k+1}$ and $s(\mu) = (v, gH_n) \in \Lambda_n^0$ then $n \geq j$ and $r(\mu) = (v, gH_{n-j}) \in \Lambda_{n-j}^0$. In particular,

$$s(\lambda') = r(\lambda'') = (x'(m), c_n(\alpha_m)^{-1}g_n) = x(m),$$

so $w\Lambda_n x(m) \neq \emptyset$. □

Lemma 5.4. *Adopt the notation and assumptions* 4.1*. Then the* $(k+1)$*-graph* $\varprojlim(\Lambda_n, p_n)$ *has no local periodicity if and only if it satisfies condition* 2 *of Theorem* 5.1*.*

Proof. First suppose that condition 2 of Theorem 5.1 holds. Fix a vertex $v \in (\varprojlim(\Lambda_n, p_n))^0$ and $p \neq q \in \mathbb{N}^{k+1}$. So $v \in \Lambda_n^0$ for some n, and v therefore has the form $v = (w, gH_n)$ for some $w \in \Lambda^0$ and $g \in \pi\Lambda$. We must show that there exists $x \in v(\varprojlim(\Lambda_n, p_n))^\infty$ such that $\sigma^p(x) \neq \sigma^q(x)$.

We first consider the case where $p_{k+1} \neq q_{k+1}$. By construction of the tower graph $\varprojlim(\Lambda_n, p_n)$, this forces the vertices $x(p)$ and $x(q)$ to lie in distinct Λ_n for any $x \in v(\varprojlim(\Lambda_n, p_n))^\infty$; in particular they cannot be equal.

Now suppose that $p_{k+1} = q_{k+1}$. If $\sigma^p(x) = \sigma^q(x)$ for every $x \in v(\varprojlim(\Lambda_n, p_n))^\infty$, then for any $\alpha \in v(\varprojlim(\Lambda_n, p_n))^{p_{k+1}e_{k+1}}$ and any $y \in s(\alpha)(\varprojlim(\Lambda_n, p_n))^\infty$, we have $\sigma^p(\alpha y) = \sigma^q(\alpha y)$; that is,

$$\sigma^{p-p_{k+1}e_{k+1}}(y) = \sigma^{q-q_{k+1}e_{k+1}}(y) \quad \text{for all } y \in s(\alpha)(\varprojlim(\Lambda_n, p_n))^\infty.$$

So we may assume without loss of generality that $p_{k+1} = q_{k+1} = 0$. Write p' and q' for the elements of $\mathbb{N}^k$ whose entries are the first k entries of p and q.

We have $v \in \Lambda_n$ for some n, so there exists $w \in \Lambda^0$ and $g \in \pi\Lambda$ such that $v = (w, gH_n)$. Suppose first that there exists $x \in w\Lambda^\infty$ such that $\sigma^{p'}(x) \neq \sigma^{q'}(x)$, then the infinite path $(x, gH_n) \in v\Lambda_n^\infty$ such that

$$(x, gH_n)(0, m) := (x(0, m), c_n(x(0, m))^{-1}gH_n) \quad \text{for all } m \in \mathbb{N}^k$$

also satisfies $\sigma^{p'}((x, gH_n)) \neq \sigma^{q'}((x, gH_n))$. By Lemma 5.2 we may choose an infinite path y such that $y|_{\mathbb{N}^k \times \{0\}} = (x, gH_n)$, and then $y \in v(\varprojlim(\Lambda_n, p_n))^\infty$ satisfies $\sigma^p(y) \neq \sigma^q(y)$.

Now suppose that every path $x \in w\Lambda^\infty$ satisfies $\sigma^{p'}(x) = \sigma^{q'}(x)$. Then by condition 2 of Theorem 5.1, we may fix $x \in w\Lambda^\infty$ and $N \in \mathbb{N}$ such that $c_N(x(0, p')) \neq c_N(x(0, q'))$. It then follows from the definition of the c_j that $c_j(x(0, p')) \neq c_j(x(0, q'))$ whenever $j \geq N$. So with $j := \max\{N, n\}$, we have

$$(x, gH_j)(p') = (x(p'), c_j(x(0, p'))^{-1}gH_j) \neq (x(q'), c_j(x(0, q'))^{-1}gH_j) = (x, gH_j)(q').$$

There is an element $g = (g_i)_{i=1}^\infty$ of $\varprojlim(G_n, q_n)$ determined by $g_i := gH_i$ for all i. Let x^g be the element of $(\varprojlim(\Lambda_n, p_n))^\infty$ determined by x and g as in Lemma 5.2. Then $(x, gH_n)((j-n)e_{k+1} + p) \neq (x, gH_n)((j-n)e_{k+1} + q)$, and therefore x^g satisfies $\sigma^p(x^g) \neq \sigma^q(x^g)$ as required. Hence condition 2 of Theorem 5.1 implies that $\varprojlim(\Lambda_n, p_n)$ has no local periodicity.

To show that if $\varprojlim(\Lambda_n, p_n)$ has no local periodicity then condition 2 of Theorem 5.1 holds, we prove the contrapositive statement. Suppose that condition 2 of Theorem 5.1 does not hold. Fix $v \in \Lambda^0$ and $p, q \in \mathbb{N}^k$ such that $\sigma^p(x) = \sigma^q(x)$ for all $x \in v\Lambda^\infty$ and $c_n(x(p,p+l)) = c_n(x(q,q+l))$ for all $n \in \mathbb{N}$, $l \in \mathbb{N}^k$. Then for each $x \in v\Lambda^\infty$ and each $g = (g_n)_{n=1}^\infty \in \varprojlim(G_n, p_n)$, we have $\sigma^p(x, g_n)(0,l) = \sigma^q(x, g_n)(0,l)$ for all $n \in \mathbb{N}$ and $l \in \mathbb{N}^k$. Hence Lemma 5.2 implies that every $y \in v(\varprojlim(\Lambda_n, p_n))^\infty$ satisfies $\sigma^{(p,0)}(y) = \sigma^{(q,0)}(y)$. $\square$

6. Projective limit k-graphs

Let $(\Lambda_n, \Lambda_{n+1}, p_n)_{n=1}^\infty$ be a sequence of row-finite coverings of k-graphs with no sources as in Section 2.3. We aim to show that the sets $(\varprojlim \Lambda_i)^m := \varprojlim(\Lambda_i^m, p_i)$ under the projective limit topology with the natural (coordinate-wise) range and source maps specify a topological k-graph (in the sense of Yeend). Moreover, we show that the associated topological k-graph C^*-algebra is isomorphic to the full corner $P_0 C^*(\varprojlim(\Lambda_n; p_n))P_0$ determined by $P_0 := \sum_{v \in \Lambda^0} s_v$. In particular, when the Λ_n and p_n are as in 4.1, the C^*-algebra of the projective limit topological k-graph is isomorphic to the crossed product of $C^*(\Lambda)$ by the coaction of the projective limit of the groups G_i obtained from Theorem 3.1.

Let $(\Lambda_n, \Lambda_{n+1}, p_n)_{n=1}^\infty$ be a sequence of row-finite coverings of k-graphs with no sources. Let $\varprojlim(\Lambda_i, p_i)$ be the projective limit category, equipped with the projective limit topology. That is, $\varprojlim(\Lambda_i, p_i)$ consists of all sequences $(\lambda_i)_{i=1}^\infty$ such that each $\lambda_i \in \Lambda_i$ and $p_i(\lambda_{i+1}) = \lambda_i$; the structure maps $\tilde{r}$, $\tilde{s}$, $\tilde{\circ}$ and $\widetilde{\mathrm{id}}$ on $\varprojlim(\Lambda_i, p_i)$ are obtained by pointwise application of the corresponding structure maps for Λ. The cylinder sets $Z(\lambda_1, \dots, \lambda_j) := \{(\mu_i)_{i=1}^\infty \in \varprojlim(\Lambda_i, p_i) : \mu_i = \lambda_i \text{ for } 1 \le i \le j\}$, form a basis of compact open sets for a locally compact Hausdorff topology.

Define $\tilde{d} : \varprojlim(\Lambda_i, p_i) \to \mathbb{N}^k$ by $\tilde{d}((\lambda_i)_{i=1}^\infty) := d(\lambda_1)$. Since the p_i are degree-preserving, we have

$$\tilde{d}((\lambda_i)_{i=1}^\infty) = d(\lambda_i) \quad \text{for all } i \ge 1.$$

For fixed $\lambda = (\lambda_i)_{i=1}^\infty \in \varprojlim(\Lambda_i, p_i)^{m+n}$, the unique factorisation property for each λ_i produces unique elements $\lambda(0,m) := (\lambda_i(0,m))_{i=1}^\infty \in \varprojlim(\Lambda_i, p_i)^m$ and $\lambda(m,n) := (\lambda_i(m,n))_{i=1}^\infty \in \varprojlim(\Lambda_i, p_i)^n$ such that $\lambda = \lambda(0,m)\lambda(m,n)$; that is, $(\varprojlim(\Lambda_i, p_i), \tilde{d})$ is a second-countable small category with a degree functor satisfying the factorisation property.

The identity $\tilde{d}((\lambda_i)_{i=1}^\infty) = d(\lambda_i)$ for all $i \ge 1$ implies that $Z(\lambda_1, \dots, \lambda_j)$ is empty unless $d(\lambda_1) = \dots = d(\lambda_j)$, and it follows that $\tilde{d}$ is continuous.

We claim that $\tilde{r}$ and $\tilde{s}$ are local homeomorphisms. To see this, fix a cylinder set $Z(v_1, \dots, v_j) \subset \varprojlim(\Lambda_i, p_i)^0$, and for $\lambda \in v_1\Lambda_1$ and $2 \le l \le j$, let $v_l p_{1,l}^{-1}(\lambda)$ be the unique element of $v_l\Lambda_l$ such that $p_1 \circ p_2 \circ \dots \circ p_{l-1}(v_l p_{1,l}^{-1}(\lambda)) = \lambda$. Then

$$\tilde{r}^{-1}(Z(v_1, \dots, v_j)) \cap \varprojlim(\Lambda_i, p_i)^n := \sqcup_{\lambda \in v_1\Lambda_1^n} Z(\lambda, v_2 p_{1,2}^{-1}(\lambda), \dots, v_j p_{1,j}^{-1}(\lambda))$$

which is clearly open, showing that $\tilde{r}$ is continuous. Moreover, this same formula shows that for $\lambda = (\lambda_i)_{i=1}^\infty \in \varprojlim(\Lambda_i, p_i)$, the restriction of $\tilde{r}$ to $Z(\lambda_1)$ is a homeomorphism, and $\tilde{r}$ is a local homeomorphism as claimed. A similar argument shows that $\tilde{s}$ is also a local homeomorphism.

It is easy to see that the inverse image under composition of the cylinder set $Z(\lambda_1, \dots, \lambda_j) \in \varprojlim(\Lambda_i, p_i)^n$ is equal to the disjoint union

$$\bigsqcup_{p+q=n} Z(\lambda_1(0,p), \dots, \lambda_j(0,p)) \times Z(\lambda_1(p,q), \dots, \lambda_j(p,q))$$

of cartesian products of cylinder sets and hence is open, so that composition is continuous, and it follows that $(\varprojlim(\Lambda_i, p_i), \tilde{d})$ is a topological k-graph in the sense of Yeend [21, 20].

Let $\varinjlim(\Lambda_n; p_n)$ be as described in Section 2.3, and let P_0 denote the full projection $\sum_{v\in\Lambda^0} s_v \in M(C^*(\varinjlim(\Lambda_n; p_n)))$. For the following proposition, we need to describe $P_0 C^*(\varinjlim(\Lambda_n; p_n))P_0$ in detail. For $n \geq m \geq 1$, we write $p_{m,n} : \Lambda_n \to \Lambda_m$ for the covering map $p_{m,n} := p_m \circ \cdots \circ p_{n-1}$, with the convention that $p_{n,n}$ is the identity map on Λ_n. For $v \in \Lambda_m^0$, and $l \leq m$, we denote by $\alpha_{l,m}(v)$ the unique path in $\varinjlim(\Lambda_n; p_n)^{(m-l)e_{k+1}}$ whose source is v (and whose range is $p_{l,m}(v)$). In particular, $\alpha_{1,m}(v)$ the unique path in $\varinjlim(\Lambda_n; p_n)^{(m-1)e_{k+1}}$ whose source is v with range in Λ_1. For $\lambda \in \Lambda_m$,

$$s_{\alpha_{1,m}(r(\lambda))} s^*_{\alpha_{1,m}(r(\lambda))} s_{p_{1,m}(\lambda)} = s_{\alpha_{1,m}(r(\lambda))} s_\lambda s^*_{\alpha_{1,m}(s(\lambda))} = s_{p_{1,m}(\lambda)} s_{\alpha_{1,m}(s(\lambda))} s^*_{\alpha_{1,m}(s(\lambda))}.$$

Furthermore, $P_0 C^*(\varinjlim(\Lambda_n, p_n))P_0$ is equal to the closed span

$$P_0 C^*(\varinjlim(\Lambda_n, p_n))P_0 = \overline{\operatorname{span}}\{s_{\alpha_{1,m}(r(\lambda))} s_\lambda s^*_{\alpha_{1,m}(s(\lambda))} : m \geq 1, \lambda \in \Lambda_m\}.$$

Proposition 6.1. *Let $(\Lambda_n, \Lambda_{n+1}, p_n)_{n=1}^\infty$ be a sequence of row-finite coverings of k-graphs with no sources, and let $\varinjlim(\Lambda_n; p_n)$ be the associated $(k+1)$-graph as in* [12]*. Let $P_0 := \sum_{v\in\Lambda_0^0} s_v \in MC^*(\varinjlim(\Lambda_n; p_n))$. Let $(\varprojlim(\Lambda_i, p_i), \tilde{d})$ be the topological k-graph defined above. Then there is a unique isomorphism*

$$\pi : P_0 C^*(\varinjlim(\Lambda_n, p_n))P_0 \to C^*(\varprojlim(\Lambda_i, p_i))$$

such that for $\lambda \in \Lambda_m$,

$$\pi(s_{\alpha_{1,m}(r(\lambda))} s_\lambda s^*_{\alpha_{1,m}(s(\lambda))}) = \chi_{Z(p_{1,m}(\lambda), p_{2,m}(\lambda), \dots, p_{m-1,m}(\lambda), \lambda)}. \tag{3}$$

In particular, with the notation and assumptions (4.1)*, the C^*-algebra $C^*(\varprojlim(\Lambda_i, p_i))$ of the topological k-graph $\varprojlim(\Lambda_i, p_i)$ is isomorphic to the coaction crossed-product $C^*(\Lambda) \times_\delta G$.*

Proof. The final statement will follow from Theorem 4.3 once we establish the first statement.

To prove the first statement we will use Allen's gauge-invariant uniqueness theorem for corners in k-graph algebras [1]. For this, we adopt Allen's notation: for $\mu, \nu \in \Lambda_1^0 \varinjlim(\Lambda_n; p_n)$, we let $t_{\mu,\nu} := s_\mu s_\nu^* \in P_0 C^*(\varinjlim(\Lambda_n; p_n))P_0$. The factorisation property guarantees that for $\mu, \nu \in \Lambda_1^0 \varinjlim(\Lambda_n; p_n)$, we can rewrite $\mu = \alpha_{1,m}(r(\mu'))\mu'$ and $\nu = \alpha_{1,m}(r(\nu'))\nu'$ for some $m \geq 1$ and $\mu', \nu' \in \Lambda_m$ with $s(\mu') = s(\nu')$. By [1, Corollary 3.7], there is an isomorphism θ of $P_0 C^*(\varinjlim(\Lambda_n; p_n))P_0$ onto Allen's universal algebra $C^*(\varinjlim(\Lambda_n; p_n), \Lambda_1^0)$ (see Definition 3.1 and the following paragraphs in [1]) which satisfies $\theta(t_{\mu,\nu}) = T_{\mu,\nu}$ for all μ, ν. It therefore suffices here to show that there is an isomorphism $\psi : C^*(\varinjlim(\Lambda_n; p_n), \Lambda_1^0) \to C^*(\varprojlim(\Lambda_i, p_i))$ such that

$\psi(T_{\alpha_{1,m}(r(\mu))\mu,\alpha_{1,m}(r(\nu))\nu}) = \chi_{Z(p_{1,m}(\mu),\dots,\mu)*Z(p_{1,m}(\nu),\dots,\nu)}$ for all $m \geq 1$ and $\mu,\nu \in \Lambda_m$ with $s(\mu) = s(\nu)$; the composition $\pi := \psi \circ \theta$ clearly satisfies (3), and it is uniquely specified by (3) because the elements $\{t_{\alpha_{1,m}(r(\lambda))\lambda,\alpha_{1,m}(s(\lambda))} : m \geq 1, \lambda \in \Lambda_m\}$ generate $P_0 C^*(\varprojlim(\Lambda_n; p_n))P_0$ as a C^*-algebra.

Let Γ denote the topological k-graph $\varprojlim(\Lambda_i, p_i)$. Since Γ is row-finite and has no sources, $\partial\Gamma = \Gamma^\infty$. As in [21], for open subsets $U, V \subset \Gamma$, let $Z_{\mathcal{G}_\Gamma}(U *_s V, m)$ denote the set $\{(\mu x, m, \nu x) : \mu \in U, \nu \in V, x \in \Gamma^\infty, s(\mu) = s(\nu) = r(x)\}$. Then $\mathcal{G}_\Gamma$ is the locally compact Hausdorff topological groupoid

$$\mathcal{G}_\Gamma = \{(x, m-n, y) : x, y \in \Gamma^\infty, m, n \in \mathbb{N}^k, \sigma^m(x) = \sigma^n(y)\}$$

where the $Z_{\mathcal{G}_\Gamma}(U *_s V, m)$ form a basis of compact open sets for the topology.

For $m \geq 1$ and $\lambda \in \Lambda_m$, let $U_{m,\lambda} := Z(p_{1,m}(\lambda), \dots, \lambda) \subset \Gamma$. So the $U_{m,\lambda}$ are a basis for the topology on $\Gamma = \varprojlim(\Lambda_i, p_i)$. Now for $m \geq 1$ and $\mu, \nu \in \Lambda_m$ with $s(\mu) = s(\nu)$, let

$$u_{\alpha_{1,m}(r(\mu))\mu,\alpha_{1,m}(r(\nu))\nu} := \chi_{Z(U_{m,\mu}*U_{m,\nu},d(\mu)-d(\nu))} \in C_c(\mathcal{G}_\Gamma).$$

Tedious but routine calculations using the definition of the convolution product and the involution on $C_c(\mathcal{G}_\Gamma) \subset C^*(\mathcal{G}_\Gamma)$ show that $\{u_{\alpha_{1,m}(r(\mu))\mu,\alpha_{1,m}(r(\nu))\nu} : m \geq 1, \mu, \nu \in \Lambda_m, s(\mu) = s(\nu)\}$ is a Cuntz-Krieger $(\varprojlim(\Lambda_n; p_n), \Lambda_1^0)$-family in $C^*(\mathcal{G}_\Gamma)$. By the universal property of $C^*(\varprojlim(\Lambda_n; p_n), \Lambda_1^0)$ (see [1, Section 3]), there is a homomorphism $\psi : C^*(\varprojlim(\Lambda_n; p_n), \Lambda_1^0) \to C^*(\mathcal{G}_\Gamma)$ such that

$$\psi(T_{\alpha_{1,m}(r(\mu))\mu,\alpha_{1,m}(r(\nu))\nu}) = u_{\alpha_{1,m}(r(\mu))\mu,\alpha_{1,m}(r(\nu))\nu}$$

for each m, μ, ν. The canonical gauge action $\beta : \mathbb{T}^k \to \mathrm{Aut}(C^*(\mathcal{G}_\Gamma))$ determined by $\beta_z(f)(x, m, y) := z^m f(x, m, y)$ satisfies $\psi \circ \gamma_z = \beta_z \circ \psi$ for all $z \in \mathbb{T}^k$, where γ is the gauge action on $C^*(\varprojlim(\Lambda_n; p_n), \Lambda_1^0)$. Proposition 4.3 of [21] shows that each $u_{\alpha_{1,m}(r(\mu))\mu,\alpha_{1,m}(r(\mu))\mu}$ is nonzero, and it follows from the gauge-invariant uniqueness theorem [1, Theorem 3.5] that ψ is injective. The topologies on $\mathcal{G}_\Gamma^{(0)}$ and on $\mathcal{G}_\Gamma$ are generated by the collections $\{U_{m,\lambda} : m \geq 1, \lambda \in \Lambda_m\}$ and $\{U_{m,\mu} * U_{m,\nu} : m \geq 1, \mu, \nu \in \Lambda_m, s(\mu) = s(\nu)\}$ respectively of compact open sets. Since $C^*(\{u_{\alpha_{1,m}(r(\mu))\mu,\alpha_{1,m}(r(\nu))\nu} : m \geq 1, \mu, \nu \in \Lambda_m, s(\mu) = s(\nu)\}) \subset C^*(\mathcal{G}_\Gamma)$ contains the characteristic functions of these sets, it follows that ψ is also onto, and this completes the proof. □

Remark 6.2. The final statement of Proposition 6.1 suggests that $\varprojlim(\Lambda_i, p_i)$ should be thought of as a skew-product of Λ by G.

To make this precise, note that for $\lambda \in \Lambda$, $c(\lambda) := (c_n(\lambda))_{n=1}^\infty$ belongs to G, and $c : \Lambda \to G$ is then a cocycle. There is a natural bijection between the cartesian product $\Lambda \times G$ and the topological k-graph $\varprojlim(\Lambda_i, p_i)$, so we may view $\Lambda \times G$ as a topological k-graph by pulling back the structure maps from $\varinjlim(\Lambda_i, p_i)$. What we obtain coincides with the natural definition of the skew-product $\Lambda \times_c G$.

With this point of view, we can regard Proposition 6.1 as a generalisation of [15, Theorem 7.1(ii)] to profinite groups and topological k-graphs: $C^*(\Lambda \times_c G) \cong C^*(\Lambda) \times_\delta G$.

Example 6.3 (Example 3.3 continued). Resume the notation of Examples 3.3 and 4.2. The resulting projective limit $\varprojlim(\Lambda_n, p_n)$ is the topological 1-graph E associated to the odometer action of $\mathbb{Z}$ on the Cantor set as in [21, Example 2.5(3)]. That is, E can be realised as the skew-product of B_1^* by the 2-adic integers $\mathbb{Z}_2$ with respect to the functor $c : B_1^* \to \mathbb{Z}_2$ determined by $c(f) = (1, 1, 1, \dots)$, where f is the loop edge generating B_1^*.

References

[1] S. Allen, *A gauge-invariant uniqueness theorem for corners of k-graph algebras*, Rocky Mountain J. Math, to appear [arXiv:math.OA/0506582].

[2] T. Bates, J. Hong, I. Raeburn, and W. Szymański, *The ideal structure of the C^*-algebras of infinite graphs*, Illinois J. Math. **46** (2002), 1159–1176.

[3] D. Drinen and M. Tomforde, *The C^*-algebras of arbitrary graphs*, Rocky Mountain J. Math. **35** (2005), 105–135.

[4] S. Echterhoff, S. Kaliszewski, J. Quigg and I. Raeburn, *A categorical approach to imprimitivity theorems for C^*-dynamical systems*, Mem. Amer. Math. Soc. **180** (2006), viii+169 pp.

[5] M. Enomoto and Y. Watatani, *A graph theory for C^*-algebras*, Math. Japon. **25** (1980), 435–442.

[6] P.A. Fillmore, *A user's guide to operator algebras*, Canadian Mathematical Society Series of Monographs and Advanced Texts, John Wiley & Sons, Inc., New York, 1996, xiv+223 pp.

[7] S. Kaliszewski and J. Quigg, *Mansfield's imprimitivity theorem for full crossed products*, Trans. Amer. Math. Soc. **357** (2005), 2021–2042.

[8] S. Kaliszewski and J. Quigg, *Landstad's characterisation for full crossed-products*, preprint (2006) [arxiv:math.OA/0601559].

[9] A. Kumjian and D. Pask, *Higher rank graph C^*-algebras*, New York J. Math. **6** (2000), 1–20.

[10] A. Kumjian, D. Pask, and I. Raeburn, *Cuntz-Krieger algebras of directed graphs*, Pacific J. Math. **184** (1998), 161–174.

[11] A. Kumjian, D. Pask, I. Raeburn, and J. Renault, *Graphs, groupoids and Cuntz-Krieger algebras*, J. Funct. Anal. **144** (1997), 505–541.

[12] A. Kumjian, D. Pask and A. Sims, *C^*-algebras associated to coverings of k-graphs*, preprint, 2006 [arXiv:math.OA/0612204].

[13] M.B. Landstad, *Duality for dual C^*-covariance algebras over compact groups*, preprint, 1978.

[14] M. Landstad, *Duality theory for covariant systems*, Trans. Amer. Math. Soc. **248** (1979), 223–267.

[15] D. Pask, J. Quigg, and I. Raeburn, *Coverings of k-graphs*, J. Algebra **289** (2005), 161–191.

[16] D. Pask, I. Raeburn, M. Rørdam and A. Sims, *Rank-2 graphs whose C^*-algebras are direct limits of circle algebras*, J. Funct. Anal. **239** (2006), 137–178.

[17] J. Quigg, *Landstad duality for C^*-coactions*, Math. Scand. **71** (1992), 277–294.

[18] D.I. Robertson and A. Sims, *Simplicity of C^*-algebras associated to higher-rank graphs*, Bull. London Math. Soc., to appear.

[19] G. Robertson and T. Steger, *Affine buildings, tiling systems and higher rank Cuntz-Krieger algebras*, J. reine angew. Math. **513** (1999), 115–144.

[20] T. Yeend, *Topological higher-rank graphs and the C^*-algebras of topological 1-graphs*, Contemp. Math. **414** (2006), 231–244.

[21] T. Yeend, *Groupoid models for the C^*-algebras of topological higher-rank graphs*, J. Operator. Th, **57** (2007), 95–120.

Ass. Prof. David Pask, School of Mathematics and Applied Statistics, University of Wollongong, Wollongong, NSW, 2522, AUSTRALIA
E-mail address: dpask@uow.edu.au

Prof. John Quigg, Department of Mathematics and Statistics, Arizona State University, Tempe, Arizona, 85287, USA
E-mail address: quigg@asu.edu

Dr Aidan Sims, School of Mathematics and Applied Statistics, University of Wollongong, Wollongong, NSW, 2522, AUSTRALIA
E-mail address: asims@uow.edu.au